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Economic Geology

and the

Bulletin of the Society of Economic Geologists

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ECONOMIC GEOLOGY

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THORIUM–URANIUM RATIOS OF ROCKS AND THEIR RELATION TO LEAD ORE GENESIS.[1]

NORMAN B. KEEVIL.

ABSTRACT.

The calculation of the atomic weights of rock leads from a new series of thorium-uranium ratios on basaltic (3.3) and granitic (2.8) rocks from widely separated localities has shown that the variation to be expected is 207.18 to 207.21, which is exactly what is found from recent isotopic analyses of a representative series of ore leads. The new results indicate that the values calculated by Holmes are too low, probably because of his including some unreliable data. This makes unnecessary the conclusion reached by Holmes that ore leads must come from a deep magmatic source, and this combined with the critical analysis of the problem by Graton would indicate that lead ores are probably derived from basaltic or granitic rocks or their magmas.

The results of thorium and uranium analyses on a series of different rocks and comparisons, using these data, with Holmes' calculations and with the chemical and physical determinations of the atomic weights of ore leads are presented in tabular form.

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[1] Paper No. 50, published under the auspices of the Committee on Geophysical Research and the Division of Geological Sciences at Harvard University.

INTRODUCTION.

THE use of variations in the isotopic constitution of lead from various sources has recently been the subject of much controversy in the problem of the genesis of lead ores. Holmes [2] observed that while common or ordinary lead extracted from such ores as galena and cerussite was apparently always the same, judging by the constancy of the atomic weight determinations, 207.21 $\pm$ 0.01, that present in granites and basalts was calculated to be of a considerably different isotopic composition. According to Holmes' calculations, any lead derived from these rocks or their magmas should have atomic weights varying between 207.10 and 207.21 for basalts, and 207.14 and 207.21 for granites, a variation that could have been easily detected by chemical or physical determinations of the isotopic constitution. The absence of any such differences in more than a dozen accurate atomic weight determinations has led Holmes to the conclusion that lead ores cannot be derived from either basaltic or granitic magmas, but must come from a much deeper source. The arguments leading to his conclusion are that, since rocks and their magmas contain lead, uranium, and thorium, the isotopic constitution of the lead would be continuously changing because of the addition of Pb^{207} and Pb^{206} from the disintegration of actino-uranium and uranium and Pb^{208} from thorium. From a consideration of the lead, thorium, and uranium content of rocks, Holmes attempts to prove that the atomic weight and isotopic constitution of rock leads have changed with time, and therefore they differ from "ore lead," which is always 207.21. Holmes assumes that "primeval lead" present at the earth's beginning (assumed to be two billion years ago), had a constant composition due to perfect "mixing," giving an over-all atomic weight of 207.21. Ore leads are then considered to be derived from a deep-lying source of "primeval lead" and to have no genetic connection with acidic and basic magmas. This, of course, implies the absence of any radioactive material in this source, as otherwise there would be a contamination increasing with time as in the case of other rocks.

[2] Holmes, A.: The origin of primary lead ores. ECON. GEOL., 32: 763–782, 1937

On the surface, the case presented by Holmes is a convincing one, although his conclusions represent a departure from the conventional picture of sulphide ore genesis. If nothing more, the paper has stimulated a new interest in the geophysical applications of radioactivity and isotopic research, and has revived discussion of the ultimate source of ore-bearing veins and the mechanics of their invasion of the earth's crust. Holmes' theory has been accepted by Knopf [3] with some reservations, and by others,[4] but has been severely criticized by Graton [5] on several grounds. Graton points out that a wealth of geological circumstantial evidence is against Holmes' theory, and emphasizes that the degree of accuracy of the data employed by Holmes is not sufficient to warrant such a revolutionary departure from accepted theories of sulphide-ore formation and petrogenesis. The theory has been questioned by Wells also.[6]

It is not the purpose of this paper to pursue further the general criticism of Holmes' paper, but to examine quantitatively the fundamental facts upon which it depends, and to apply to these new, more accurate data. It is shown that neither of Holmes' two main postulates is consistent with these recent experimental results, and that his conclusions seem, therefore, untenable.

THORIUM-URANIUM RATIOS IN ROCKS.

No accurate atomic weight or isotopic analysis of rock lead has ever been made. The values used by Holmes were calculated from average values of the lead, uranium, and thorium content of granitic and basaltic rocks. His entire theory rests upon his choice of lead and radioactivity determinations used for his averages. The determination of the lead content is difficult, but is a straightforward chemical procedure. Hevesy and Hobbie [7]

[3] Knopf, A.: ECON. GEOL., 32: 1061–1064, 1937.

[4] Kelley, V. C.: ECON. GEOL., 32: 1005, 1937.

[5] Graton, L. C.: Ores: from magmas, or deeper? A reply to Arthur Holmes. ECON. GEOL., 33: 251–286, 1938.

[6] Wells, R. C.: ECON. GEOL., 33: 216–217, 1938.

[7] Hevesy, G., and Hobbie, R.: Lead content of rocks. Nature, 128: 1038–1039, 1931.

find as an average for two hundred and twenty-one samples 16×10^{-6} gram of lead per gram of rock, for fifty-eight granites 30×10^{-6}, and for sixty-eight basalts and gabbros 5×10^{-6} gram of lead per gram, and these results may be sufficiently representative for the present problem.

The real difficulty comes in the choice of representative determinations of rock radioactivities. Holmes plots " all of the available analytical data for thorium and uranium," and gives reference to the computations by Jeffreys [8] and Urry,[9] both of which are subject to large errors. The values given by Jeffreys represent the uncritical averaging of all radioactivity determinations, and thus have no significance. Similarly, the values reported by Urry are subject to correction.[10] Since large errors are known to exist in many previous radioactivity determinations, averages based on such data cannot be used for the accurate calculation of atomic weights of rock leads, nor for the basis of a theory on such a derived difference as 207.14 and 207.21. Furthermore, it does not seem practicable to attempt to evaluate the mass of data from different laboratories until the international interchecking program initiated by Professor R. D. Evans has been completed. In the following, a new series of radium and thorium determinations will be used to calculate more accurately the atomic weights of rock leads.

Experimental Notes.

The uranium and thorium results reported below were determined in the course of a series of helium age determinations on fresh igneous rocks [11] that were carefully selected for this purpose at some depth from the surface, so that they were free from all

[8] Jeffreys, H.: On the radioactivities of rocks. Gerlands Beiträge Z Geophysik, 47: 149–170, 1936.

[9] Urry, W. D.: The occurrence of radium, uranium, and potassium in the earth. Proc. Am. Acad. Arts and Sci., 68: 137–144, 1933.

[10] Evans, R. D., Goodman, C., Keevil, N. B., Lane, A. C., and Urry, W. D.: Phys. Rev., in press.

[11] The results of this research on helium ages carried out at the Massachusetts Institute of Technology and commenced under a Fellowship in Geological Sciences awarded by the Royal Society of Canada are appearing in other journals.

alteration. The uranium content was obtained by determining the amount of radium present in the rock (as all members of the radioactive series are in equilibrium in all but the most recent rocks). The conversion factor used was

$$U = 2.70 \times 10^{6}\ Ra.$$

The radium was determined experimentally by measuring the buildup of charge due to the ionization of radon by means of a Compton electrometer with a sensitivity of about 5.2×10^{-4} volts per millimeter on the glass scale used for visual observations. A compensating chamber was used to reduce the background effect to a minimum. The apparatus was calibrated with four different standard solutions of known radium content, on an average of twice a month while the determinations were being made. Intercomparisons were made, with radium determinations on twelve different rock specimens, with Goodman working in Evans' laboratory, and good agreement was obtained. The latter apparatus was also carefully calibrated throughout the course of the work. The accuracy of both sets of calibrations was sufficient to show discrepancies between different "standard" solutions. The selection of an accurate international standard is discussed elsewhere in the detailed report of the above work.[10] It has been checked by several methods by a number of different workers on several apparatuses.

The thorium determinations were made by the streaming method, measuring the alpha-particle emission from thoron by use of a vacuum-tube amplifying circuit, and recording the electrical impulses photographically on a revolving drum driven by a Telechron motor. Calibrations were made from an analysed monazite, treated in exactly the same way as a rock, and also from a carefully prepared thorium solution (in equilibrium). Calibrations were made, on the average, twice a month while these experiments were in progress. The values obtained on a suite of rocks were in good agreement with those obtained indirectly by Goodman by the alpha-count method from deposited thin films of the rock.[10, 12]

[12] Evans, R. D., and Goodman, C.: Phys. Rev., in press.

New Results for Basaltic and Granitic Rocks.

The results obtained have been grouped for the present purpose into basic rocks and acidic rocks, in Tables I and II. The probable errors of individual determinations are about 5 per cent, being less for samples with high activities, and greater for low concentrations.

TABLE I.

THORIUM-URANIUM RATIOS FOR BASALTIC TYPE ROCKS.

Locality	Age	U × 10^6 gram per gram	Th × 10^6 gram per gram	Th/U
Bear Tooth Range, Wyo.	Tertiary	1.12	4.30	3.8
Oldwick, N. J.	Triassic	0.62	2.26	3.6
Kilchattan, Scotland	Late Paleozoic	0.98	3.42	3.5
Reasagbuie, Scot.	Late Paleozoic	1.94	4.40	2.3
Eustis Mine, Que.	Late Paleozoic ?	1.27	2.93	2.3
Eustis Mine, Que.	Early Paleozoic ?	0.62	1.61	2.6
St. George, N. B.	Paleozoic	0.49	1.70	3.5
Bear Tooth Range, Wyo.	Keweenawan or later	1.27	5.05	4.0
Noranda, Que.	Keweenawan	1.33	2.43	1.8
Gogebic Range, Wis.	Late Precambrian	0.40	1.72	4.3
Ropruchei, U. S. S. R.	Late Precambrian	0.77	2.04	2.7
Quad Creek, Wyo.	Early Precambrian	0.45	2.13	4.7
Average for twelve specimens		0.94	2.83	3.2
Average for three European rocks		1.23	3.28	2.8
Average for three Pacific North American rocks		0.95	3.83	4.1
Average for six East North American rocks		0.79	2.28	3.0
Average for three groups		0.99	3.13	3.3
Average for two Post Paleozoic rocks		0.87	3.28	3.7
Average for six Paleozoic rocks		1.09	3.35	3.0
Average for four Precambrian rocks		0.74	2.08	3.4

Although it would be desirable to have more determinations, the average value of Th/U is probably not far off, and is close to that being selected for the National Research Council's forthcoming Handbook of Geophysics. It is significant that the range of fluctuation of individual determinations is not large, and that the thorium-uranium ratios of basalts calculated for dif-

ferent continental regions and for different geological eras do not differ appreciably from the total average. The largest difference is between the rocks of the Canadian Precambrian Shield and other granitic rocks and the indications are that the former are lower than usual in radioactivity. Earlier radium results by Evans [13] are in agreement with this observation.

TABLE II.

THORIUM-URANIUM RATIOS FOR GRANITIC TYPE ROCKS.

Locality	Age	U × 10^6 gram per gram	Th × 10^6 gram per gram	Th/U
Fitchburg, Mass.*	Late Paleozoic	2.5	10.1	4.2
Chelmsford, Mass.*	Late Paleozoic	8.0	14.0	1.7
Quincy, Mass.†	Paleozoic	3.05	10.6	3.7
Cape Ann, Mass.	Paleozoic	5.17	19.3	3.7
Franklin, Maine	Paleozoic	3.55	8.84	2.5
Hampstead, N. B.	Paleozoic	4.40	17.0	3.9
Kingston, Ont.	Precambrian	1.4	3.1	2.3
East of Taschereau, Que.	Precambrian	1.59	4.4	2.8
West of Taschereau, Que.	Precambrian	0.58	0.9	1.5
East of Lake LaMotte, Que.	Precambrian	1.25	2.04	1.6
North of Varsan Tp., Que.	Precambrian	0.72	2.2	3.1
Gananoque, Ont.	Precambrian	1.05	2.82	2.7
Average of twelve specimens		2.77	7.94	2.8
Average of six Paleozoic granites		4.44	13.3	3.3
Average of six Precambrian granites and granodiorites		1.1	2.6	2.3

* Average of granite and associated pegmatite.
† Average of nine consistent determinations.

THE ATOMIC WEIGHT OF ROCK LEAD.

These results will now be applied to the rock lead problem, to find how they agree with Holmes' calculations. This comparison can best be made by showing the results in tabular form. This is done in Table III. The atomic weight of the radiogenic lead can be calculated simply from the thorium-uranium ratios. The ratio of thorium lead to uranium lead now being produced in rocks is 0.336 Th/U (Table III). The resultant atomic weight for the total rock lead (the concentration of which is found from the analyses of Hevesy and Hobbie) is obtained by

[13] Evans, R. D., and Raitt, R. W.: Phys. Rev., 48: 171–176, 1935.

weighting the radiogenic lead with the more abundant common lead (207.21).[14]

The values calculated with the new results are quite different from those obtained by Holmes. The most significant fact is that the differences expected by Holmes between the atomic weights of rock leads and ore leads are not verified. This is partly because of the smaller radioactivity of these rocks than

TABLE III.

COMPARISON OF HOLMES' CALCULATIONS WITH THOSE FROM NEW THORIUM-URANIUM RATIOS.

Datum	Holmes	New results
Average U content of granites	6×10^{-6} gm./gm.	2.8×10^{-6} gm./gm.
Average U content of basalts	1.8×10^{-6} gm./gm.	0.95×10^{-6} gm./gm.
Average Th content of granites	10×10^{-6} gm./gm.	7.9×10^{-6} gm./gm.
Average Th content of basalts	4.3×10^{-6} gm./gm.	2.8×10^{-6} gm./gm.
Th/U for granites	1.7	2.8
Th/U for basalts	2.4	3.3
Th lead/U lead now being generated in granites	$1.7 \times 0.36 = 0.61$	$2.8 \times 0.33^{*} = 0.93$
Th lead/U lead now being generated in basalts	$2.4 \times 0.36 = 0.86$	$3.3 \times 0.33 = 1.09$
Average atomic weight of Pb now being generated in granites	$\frac{(0.61 \times 207.96) + 206}{1.61} = 206.74$	$\frac{(0.93 \times 207.96) + 206}{1.93} = 206.94$
Average atomic weight of Pb now being generated in basalts	$\frac{(0.86 \times 207.96) + 206}{1.86} = 206.91$	$\frac{(1.09 \times 207.96) + 206}{209} = 207.02$
Lead produced in granites in 2×10^{9} years	3.8×10^{-6} gm.	1.9×10^{-6} gm.
Lead produced in basalts in 2×10^{9} years	1.34×10^{-6} gm.	0.7×10^{-6} gm.
Atomic weight of granitic lead †	207.15	207.19
Atomic weight of basaltic lead †	207.10	207.18

* Using $\lambda Th = 1.581 \times 10^{-18}$ sec.$^{-1}$ and $\lambda U = 4.82 \times 10^{-18}$ sec.$^{-1}$.
† Using lead analyses by Hevesy and Hobbie.[7]

those taken by Holmes, but largely because of the fact that the thorium-uranium ratios are such that the combination of the radiogenic leads Pb^{208}, Pb^{207}, and Pb^{206} formed throughout geologic time results in an over-all atomic weight of nearly 207.21. When earlier reliable results [13, 15] are combined with the above data, the thorium-uranium ratio is found to be higher. This shows that, if anything, our values are a little lower than the true

[14] The change of Th/U with time has been neglected, as it would affect the results by less than .01 atomic weight unit, and this small error would tend to be compensated by the locally higher Th/U ratios indicated by the results of Evans and coworkers on some Pacific coast rocks.

[15] Finney, G. D., and Evans, R. D.: Phys. Rev., 48: 503, 1935.

rock average, and further that the values used by Holmes are much too low. It should be noted that a Th/U ratio of 4 would give a resultant atomic weight of 207.21 for radiogenic lead. That the true average of Th/U is within the range 3 to 4 is indicated further by the results obtained in some recent isotropic studies of leads from various sources.

THE ISOTOPIC CONSTITUTION OF LEAD.

The results just reported by A. O. Nier [16] on the precision mass-spectrographic studies of leads varying widely both in age and regional distribution have shown that common lead has indeed a variable isotopic constitution as suspected by many students of ore geology.[17] This contradicts Holmes' fundamental assumption that somewhere in the earth there is a source free from radioactivity which contains lead of constant isotopic composition of mass 207.21 which is responsible for all ore leads. However, it is in agreement with Holmes' thesis that ore leads from granitic or basaltic rocks or their magmas should possess a variable composition depending on the time of their concentration and upon the relative proportions of lead, uranium, and thorium present in the source.

The variations, however, are not on the scale supposed by Holmes, but are in agreement with those predicted from the present results in that they are such as to give a resultant atomic weight varying within narrow limits, and not far from 207.21. The data on the isotopic constitution of common leads from both the mass-spectrographic method and the atomic-weight method are summarized in Table IV.

Nier assumes tentatively for purposes of calculation that the lead from Great Bear Lakes represents "primeval" lead. This is certainly not strictly primeval because the Great Bear ore is younger than the first rocks to be formed in the earth's crust, and so must have had radiogenic lead added to it from the earth's

[16] Nier, A. O.: The isotopic constitution of lead from various sources. J. Am. Chem. Soc., 60: 1571, 1938.

[17] Newhouse, W. H., and Buerger, M.: Private communication, 1937. Graton, L. C.: Econ. Geol., 33: 253, 263, 268, 271, 1938.

beginning, and it is an unfortunate choice in that this particular lead comes from a region in which uranium minerals are common. Nevertheless, this lead can be chosen as a basis for comparison of the isotopic constitution of other leads, and when this is done, Nier finds that the theory of contamination of ore leads by radiogenic leads is a reasonable one. A significant observation is that the thorium-uranium ratios in the source from which the contaminating radiogenic lead was formed was on the average 3.35 (Table IV). This is consistent with the values found for the ratios in granitic and basaltic rocks (Tables I and II), and shows that ore leads could very well be derived from the magmas of these rocks.[18]

TABLE IV.

COMPARISON OF PHYSICAL AND CHEMICAL METHODS OF DETERMINING THE ISOTOPIC CONSTITUTION OF LEAD.*

Source of lead	Locality	Geological age	Isotopic abundance referred to Pb^{204} as 1.000			Excess Th lead / U lead	Atomic weight	
			Pb^{206}	Pb^{207}	Pb^{208}		Physical	Chemical
Wulfenite and Vanadinite.	Tucson Mts., Ariz.	Miocene	18.40	15.53	38.1	1.13	207.204	207.22
Cerussite.....	Wallace, Ida.	Late Cretaceous	15.08	15.08	35.07		207.214	207.21
			16.10	15.13	35.45		207.217	207.21
Lead-silver ore	Coeur d'Alene, Ida.	Late Cretaceous						207.218
								207.212
Galena.....	Metalline Falls, Washington	Late Cretaceous	19.30	15.73	39.5	1.25	207.203	207.21
Galena.....	Tetiche, U. S. S. R.	Permian						207.216
Galena.....	Joplin, Mo.	Late Carboniferous	21.65	15.88	40.8	0.96	207.178	207.22
			21.60	15.73	40.3	0.89	207.175	
			21.65	15.75	40.45	0.89	207.175	
Cerussite.....	Eifel, Germany	Carboniferous	18.20	15.46	37.7	1.06	207.203	207.20
Galena.....	Nassau, Ger.	Carboniferous	18.10	15.57	37.85	1.17	207.206	207.21
Galena.....	Yancey Co., N. Carolina	Late Precambrian	18.43	15.61	38.2	1.16	207.204	207.209
Cerussite.....	Broken Hill, N. S. W.	Precambrian	15.92	15.30	35.3		207.217	207.21
			15.93	15.28	35.2		207.216	
Galena.....	N. S. W.	Precambrian	16.07	15.40	35.5		207.217	
Galena.....	Great Bear Lake	Precambrian	15.93	15.30	35.3		207.218	207.205
			17.38	15.44	37.3	1.45	207.213	
Galena.....	Saxony, Germany	?	17.34	15.47	37.45	1.45	207.215	
					Average:	1.13		
					Th/U = 1.13/0.336 = 3.35			

* After Nier and Holmes.

18 That the ratio is closer to our average value for basalts is not considered important with the present number of determinations.

RANGE IN ATOMIC WEIGHTS OF ROCK AND ORE LEADS.

On the contamination theory, one would expect the leads first formed on the earth to have an atomic weight close to that of primeval lead, assumed to be 207.21. Lead minerals formed at successively more recent times should have an increasing amount of contamination by the radiogenic lead formed from rock or magmatic uranium and thorium, and slight changes in the atomic weight (unless the Th/U is exactly that to give 207.21). For a lead formed at the present day from a granitic magma, our results indicate that it should be 207.19. This difference of 0.02 is hardly large enough to be used with confidence, and all that can be said is that the older minerals examined by the mass spectrograph method have shown the least contamination, that is, the lowest proportion of the radiogenic lead isotopes in proportion to the index Pb^{204} of non-radiogenic origin, and that the ranges observed for different leads are just what our results would predict if the leads were derived from rock magmas, but are considerably different from those calculated by Holmes. The ranges expected, and those found experimentally, are shown in Table V.

TABLE V.

VARIATION IN THE ATOMIC WEIGHTS OF ORE AND ROCK LEADS.

	Rock lead		Ore lead	
	Calculated by Holmes with uncritical averages	Calculated above with new results	Physical method	Chemical method
Granitic rocks.....	207.14–207.21	207.19–207.21	207.175–207.218	207.20–207.22
Basaltic rocks.....	207.10–207.21	207.18–207.21		

Because of their higher lead contents, granitic rocks may have fairly large fluctuations in their uranium and thorium contents, and still result in an atomic weight close to 207.21 for rock lead. When the results of the fifty radioactivity determinations on granites selected for the Geophysical Handbook are used, the expected range in the atomic weight of granitic leads is no greater than that found with the above data. Variations in the amounts

of lead, uranium, and thorium in basalts, however, might change the expected range appreciably (unless the Th/U ratio were always close to four) because of the smaller lead contents. The fact that no large range is found experimentally might suggest that ore leads are genetically related to granites rather than to basalts. While this is in agreement with the facts of geology, the experimental results are yet too meagre to warrant considering this as any more than a suggestion.

This paper can hardly be the final word on this phase of the lead problem, but it indicates that the average Th/U ratios for rocks may well be higher than those used by Holmes, and this is suggested by recent results obtained with well standardized apparatuses. These results, combined with the recent critical analysis of Holmes' paper by Graton, would indicate a high probability that ore leads are derived, directly or indirectly, from basaltic or granitic rocks or their magmas.

HARVARD UNIVERSITY,
CAMBRIDGE, MASS.,
July 1, 1938.

ESTIMATING SAFE YIELD AS ILLUSTRATED BY THE EL PASO, TEXAS, GROUND-WATER INVESTIGATION.[1]

A. N. SAYRE.

ABSTRACT.

The El Paso investigation illustrates the methods used in estimating safe yield. The ground water occurs in a basin that is closed and except for the Rio Grande there is no outflow and very little inflow. The pumpage is well centralized near El Paso and the total pumpage to date can be estimated. A contour map of the water table was prepared from which the volume of the cones of depression or of the unwatered material was calculated. The weighted average specific yield of the unwatered deposits was computed from laboratory tests on samples from test wells and the volume of water released from storage in the formation of the cones of depression was shown to be only a fraction of the total pumpage. Current records of all the pumpage in the area are being obtained and the depth to water is measured each month in a large number of selected wells in order that the conclusions regarding the water available from recharge and the water available from storage may be checked.

A RECENT investigation of the ground-water supplies of the El Paso, Texas area made by Penn Livingston and myself affords an example of some of the problems encountered in estimating the probable future yield of ground-water reservoirs. The city of El Paso (pop. 102,421) is located on the Texas side of the Rio Grande. Juarez, on the south side of the river in Mexico, has a population of 39,375.

The cities of El Paso and Juarez and the industries located in the area draw their water supplies from wells, most of which are 600 to 800 feet deep. The total pumpage was about 16½ million gallons a day in 1937. Since the entire flow of the Rio Grande is already pre-empted for irrigation or other uses and the use of water from the river for city supplies would involve

[1] Published by permission of the Director, Geol. Survey. Presented before the Society of Economic Geologists, Washington Meeting, Dec. 28, 1937.

condemnation proceedings against some of the irrigators and the expenditure of large sums of money for treating plants and pipe lines, the determination of the quantity of water available from wells is vitally important to the citizens of the area. They have recognized the desirability of this for some time, but the immediate necessity for this information became apparent in 1934, when the water from El Paso City well No. 3 showed an abrupt increase from about 250 to over 400 parts per million of chloride and attempts to repair the well so as to exclude the water containing high chloride resulted in further increases in the chloride content of the water. Since, in the ten-year period ending in 1934, the Montana field, in which No. 3 well is located, yielded 43 per cent of all of the water pumped in the area, the failure of one of the largest wells in this field suggested that perhaps the fresh water-bearing beds had been contaminated. At the request of the El Paso authorities, W. N. White, of the Geological Survey, made a preliminary investigation in December, 1934 and a more detailed investigation was begun in July, 1935 under a cooperative agreement between the Geological Survey, the El Paso Water Board and the Texas State Board of Water Engineers.

The main objectives of the investigation were the determination of whether the beds yielding fresh water were being seriously contaminated by highly mineralized water, the quantity of water available for wells from recharge and underflow and from groundwater storage, and the location of favorable sites for the location of additional wells.

During the course of the investigation the geology of the area was studied with particular reference to the occurrence and source of the ground water. All of the available well data were collected and studied. The well data included logs of wells, records of casing and screen settings, developed capacity of the wells, total pumpage from wells, depth to the water level measurements and the altitude of the measuring points of each well that could be measured. Monthly water-level measurements were made in selected wells. Pumping tests were made to determine the permeability and specific yield of the water-bearing beds. Nu-

merous shallow test wells were bored in the valley to determine the slope of the water table and the character of the water. Deep test wells were drilled to obtain samples of the water-bearing materials for the determination of permeability and specific yield. Water samples were collected from most of the wells in the area for chemical analysis, and tests were made to determine the character of the water from various beds by electrical conductivity and by chloride and hardness determinations made in the field on samples of water collected at intervals from wells that were pumped after being idle for a considerable period.

Resistivity measurements were made by J. H. Swartz and E. L. Stephenson at nearly 200 stations along two major traverses, one of which crossed the Hueco Bolson from the Franklin Mountains to the Hueco Mountains and the other extended from the El Paso Valley to the New Mexico State Boundary. Measurements were also made along several shorter traverses. The resistivity measurements supplemented more direct information from other sources on the location and extent of the areas in which highly mineralized water occurs, and on the location of faults.

A report giving the results of these investigations was released in manuscript in January 1937 and may be consulted in the offices of the Texas State Board of Water Engineers in Austin, Texas, and of the Geological Survey in Washington.

GENERAL GEOLOGY.

Richardson [2] has described the geology and geomorphology of the area in considerable detail.

The mountains are composed of consolidated rocks that contain little or no potable ground water. The Hueco Bolson is underlain by unconsolidated sediments which, in general, yield potable water (Fig. 1). The Hueco Bolson is a north-south trending structural basin partly filled with outwash from the mountains. It is surrounded by mountains, which are separated by comparatively low debris-filled passes on all sides except the north where it is separated from the Tularosa Basin by a low trans-

[2] Richardson, G. B.: Geol. Atlas, El Paso Folio. U. S. Geol. Surv., no. 166, 1909.

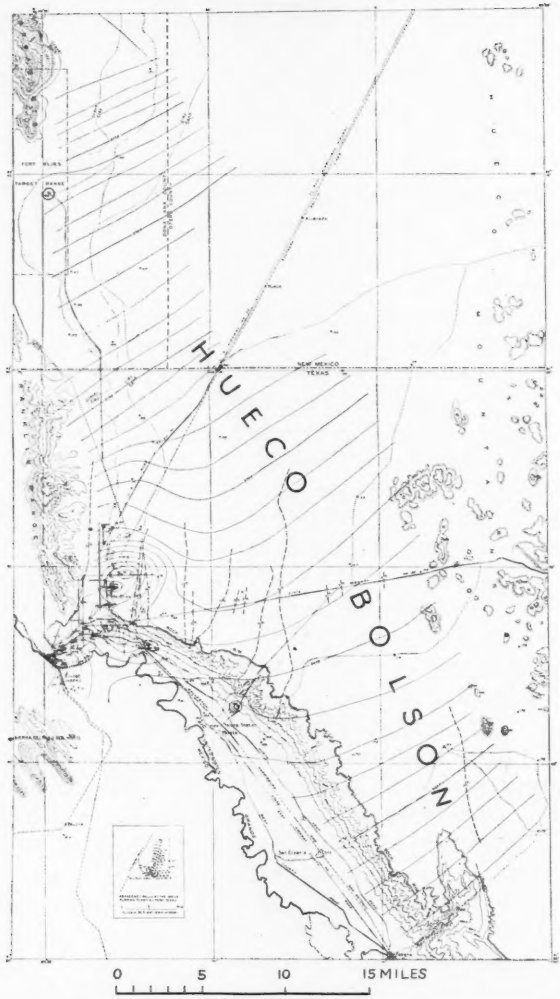

FIG. 1. Map of the El Paso, Texas, area showing the location of record wells and contours on the water table in June, 1936.

verse divide.[3] The Hueco Bolson is divisible into two parts, the upland area, locally called "The Mesa" and the valley of the Rio Grande, called the "El Paso Valley." The El Paso Valley is a broad, flat-bottomed valley 5 to 8 miles wide and from 225 to 350 feet deep, that has been incised obliquely across the bolson. The river enters the area through a narrow rock-walled gorge just above El Paso and leaves it through a similar gorge at the south end of the Quitman Mountains about 90 miles southeast of El Paso.

The Mesa surface is nearly smooth, but there are several narrow, shallow, north-south trending depressions and near the sides of the Mesa the surface rises rapidly toward the mountains. The Mesa has no surface drainage except near the El Paso Valley where numerous draws form re-entrants in the valley wall. Most of the Mesa is covered with sand, but the depressions are floored with clay. A belt 2 to 3 miles wide near the Franklin Mountains and a much narrower belt near the Hueco Mountains are covered with gravel.

A layer of dense, hard caliche 2 to 5 feet thick underlies the Mesa within a few feet of the surface. The beds of sand, gravel and clay that underly the Mesa are believed to have a combined thickness of more than 4,900 feet.[4] In general sand and gravel predominate from the surface to a depth of about 250 feet and constitute about 50 per cent of the sediments from about 250 to about 750 feet, but below 750 feet clay predominates. The beds commonly vary from 20 to 40 feet in thickness and are extremely irregular. As shown in Fig. 2, none of them appear to have any great lateral extent, and it is difficult to correlate beds even in adjacent wells. The bolson sediments were derived from the adjacent mountains, but in the El Paso valley there is believed to be 100 to 250 feet of river alluvium.

[3] Meinzer, O. E.: Geology and ground-water resources of the Tularosa Basin, New Mexico. U. S. Geol. Surv. W. S. P., no. 343.

[4] King, P. B.: Outline of the structural development of Trans-Pecos Texas. A. A. P. G., Bull., vol. 19, p. 253, 1935.

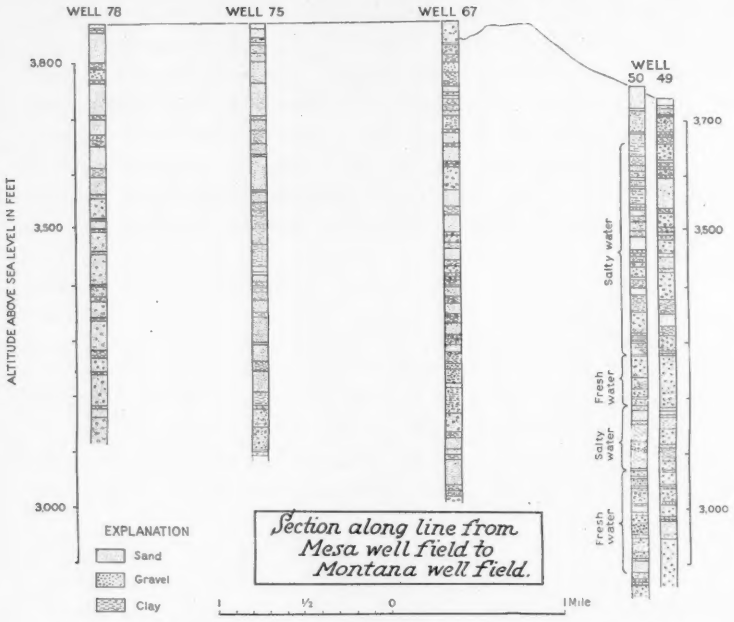

FIG. 2. Graphic logs of wells along a line from the Mesa well field to the Montana well field.

GROUND-WATER CONDITIONS.

Beneath the Mesa, the ground-water contains less than 500 parts per million total dissolved solids and occurs under water table conditions, the depth to the water level being from about 200 to 350 feet. In the lowest parts of the El Paso Valley the water level is nearly at the surface. In the valley, the quality of the water varies greatly, both vertically and laterally. To a depth of 400 to 500 feet it is in general too highly mineralized for municipal use, but below 500 feet there are several beds that yield good water. The water level in the shallow beds is in places 20 feet higher than the water level in the deeper beds that contain fresh water (Fig. 3).

Recharge to the shallow water of the El Paso Valley occurs from the Rio Grande (Fig. 4), and if the level of the fresh water continues to decline, this recharge will eventually force the highly mineralized water laterally and perhaps downward into the beds bearing fresh water.

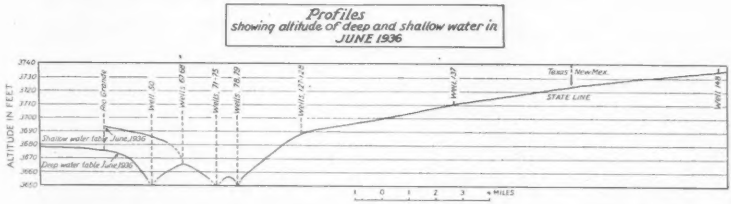

FIG. 3. Profiles showing altitude of deep and shallow water in June, 1936.

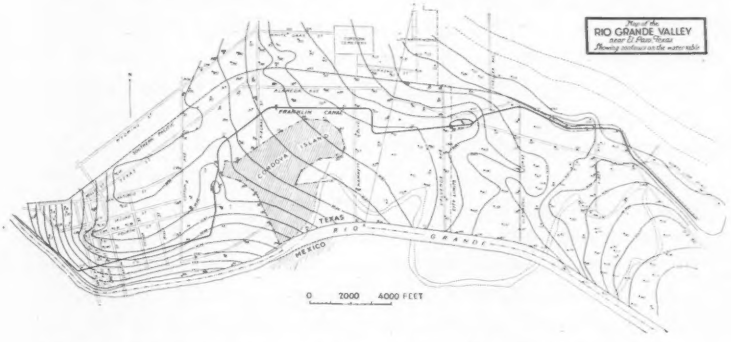

FIG. 4. Map of the Rio Grande Valley near El Paso showing contours on the water table.

INVESTIGATIONS.

The explorations made on well No. 3 by methods described by Livingston and Lynch [5] showed that highly mineralized water was entering the well through a hole in the casing at a depth of 127 feet, where there is known to be a salt-water stratum. When

[5] Livingston, P., and Lynch, W.: Methods of locating salt-water leaks in water wells. U. S. Geol. Surv. W. S. P., no. 796–A, 1937.

the casing was repaired, the chloride content of the water from the well was reduced to 280 parts per million, which is about normal for the field, and the well was put back into service. This work showed that in the principal productive beds the water is still fresh. However, the chloride content in all of the wells has been increasing gradually for many years and it is apparent that eventually the pumpage from the field must be materially reduced.

When the investigation was begun, it was realized that if recharge to the water-bearing beds occurred over the entire sand area of the Mesa, the total amount of the recharge would be very large. Therefore, a number of test holes and trenches were dug on the Mesa and samples of the materials encountered were tested for moisture content. It was found that in most of the holes the percentage of moisture increased rather rapidly from the surface to the top of the caliche, but decreased sharply below the top of the caliche. It was also observed that the roots of the desert plants generally follow along the top of the caliche, the Mesquite roots extending as much as forty feet, but rarely penetrate it. Both of these observations indicate that the caliche retards the downward movement of the water. There are numerous pipes that pass through the caliche and the caliche is thin or absent in the depressions, and some water may penetrate the caliche in some of these places, but it appears that the recharge from the sand areas is small. Moreover, the contour map of the water table shows a hydraulic gradient toward the southeast which indicates that the principal recharge occurs along the east slopes of the Franklin and Organ Mountains (Fig. 1). The average annual rainfall at El Paso is only 8.86 inches and the rains are torrential and localized. It is, therefore, difficult to determine the amount of water that is lost by seepage through the gravel slopes from torrential streams, but such observations as could be made show clearly that the losses are large. Recharge also occurs along the northeast slope of the Sierra del Paso del Norte in Mexico. Some water may enter the area by underflow from the valley of Samalayuca in Mexico, around the south end of Sierra del Paso

del Norte, but there is apparently little or no water entering the area through the other mountain passes. Slichter[6] has shown that the underflow in the El Paso gorge is very small.

In addition to the water received perennially as recharge to a ground-water reservoir a large amount of water is taken from storage in the development of the reservoir. During the early stages of this development a large part of the water that is pumped is recovered from the storage because a cone of depression is being formed. As this cone enlarges, water moves toward the well from greater distances and an increasing proportion of the water that is pumped is taken from recharge.

Two cones of depression have been formed by the pumpage in the El Paso area (Fig. 5). One of these centers in the Mesa well field, on the Mesa about 2 miles north of the El Paso Valley, and the other centers in the Montana well field in the valley about three-fourths of a mile south of the valley wall.

It is estimated that about 90,000 acre-feet of water have been pumped from the wells on the Mesa. The volume of the cone of depression was calculated to be about 125,000 acre-feet and the specific yield of the unwatered materials was calculated to be about 17 per cent. On this basis the volume of water released from storage in the formation of this cone was computed to be about 22,000 acre-feet or about one-fourth of the total pumpage, leaving about three-fourths of the water as recharge. It should be recognized that the volume of the cone may be somewhat larger than the volume computed here, because, due to the scarcity of wells east and west of the Mesa field, the edges of the cone in these directions are poorly defined. About 210,000 acre-feet of water have been pumped from the cone of depression in the El Paso Valley in and near El Paso. The volume of this cone cannot be fully determined because there are no deep wells southeast or northwest of the center of the cone, but it is certainly not large enough to have supplied all of the water that has been pumped from it, and it is believed that a quantity of water of the order of

[6] Slichter, C. S.: Observations on the ground waters of the Rio Grande Valley. U. S. Geol. Surv. W. S. P., no. 141, pp. 9–13, 1905.

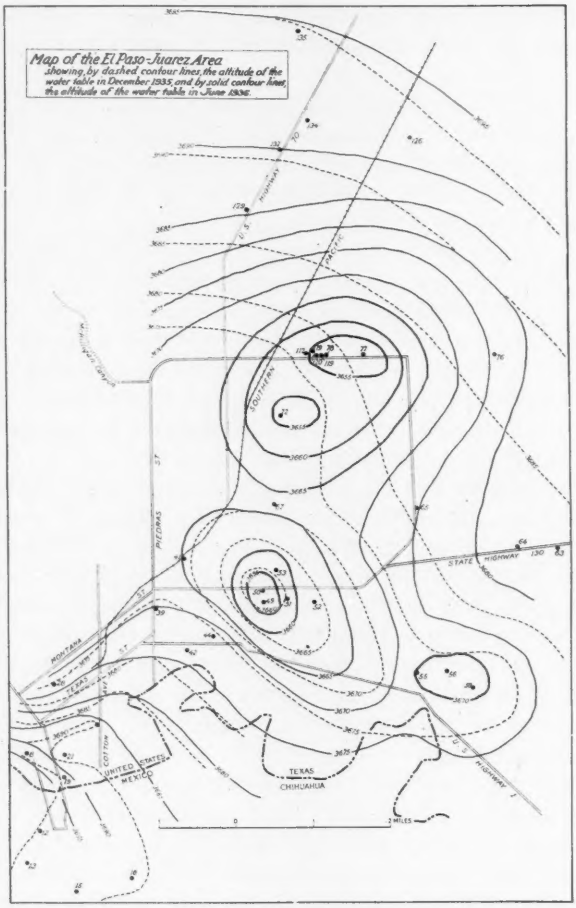
Map of the El Paso-Juarez Area
showing, by dashed contour lines, the altitude of the water table in December 1935, and, by solid contour lines, the altitude of the water table in June 1936.
SOUTHERN
PECOS
STATE HIGHWAY 130
TEXAS
CHIHUAHUA
UNITED STATES
MEXICO
COTTON
3 MILES

FIG. 5. Map of the El Paso area showing the altitude of the water table in Dec., 1935, by dashed contour lines and in June, 1936, by solid contour lines.

perhaps one-third of the total pumpage has been taken from storage and the remainder has come from recharge.

The pumpage in and near El Paso increased from about one million gallons a day in 1906 to about 15.4 million gallons a day in 1935, and has increased further during the past two years (Fig. 6).

During 1936–1937 the water level has declined, both in the valley and on the Mesa, showing that a considerable part of the increase in pumpage in these years was taken from storage.

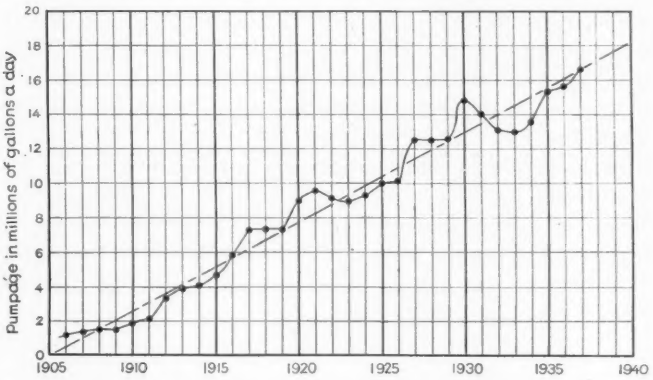

FIG. 6. Average daily pumpage from wells in the El Paso area, including Juarez, 1906 to 1937.

The cones of depression near El Paso now extend nearly half of the distance across the bolson, and moreover the sand becomes finer and the water-bearing beds of sand become thinner toward the east. Therefore, it is concluded that considerably more than half, possibly three-fourths, of the water moving from the recharge areas is at present diverted toward the pumped areas, and it is believed that if, in the future, the entire water supply is to be obtained from wells, it will be necessary to make further drafts on the storage.

Computations were made of the amount of water that would be recovered from storage if for a distance of ten miles north of

the Mesa field the water level in a series of wells were drawn down the same amount as the present drawdown in the wells of the Mesa field. It was found that the volume of the depression would be 1,460,000 acre-feet and that the amount of water that would be released by the unwatering of this volume of material, assuming an average specific yield of 17.5 per cent, would be 253,000 acre-feet. This quantity of water is equal to 15,000,000 gallons a day for a period of 15 years. It is, of course, available in addition to the annual recharge.

Measurements of the depth to water in selected wells have been made at monthly intervals since the beginning of the present investigation and records of the pumpage in the area have been obtained, and chemical analyses have been made of samples of water collected at six-month intervals from selected wells. These observations are being continued and within a few years the record will be of sufficient length for accurate determination of the validity of the above conclusions. These records, if continued, will also give advance warning of conditions that would require decreasing the pumpage in existing wells or the development of new wells many years before the actual need for such changes arises.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
June 13, 1938.

DOLOMITE AND JASPEROID IN THE METALINE DISTRICT, NORTHEASTERN WASHINGTON.*

C. F. PARK, JR.

ABSTRACT.

The replacement ore bodies of the Metaline zinc-lead district, in northeastern Washington are limited to the greatly disturbed fault block through which the Pend Oreille River flows and are associated with the major faults but are not in them. They are mostly near the top of the Metaline limestone, of Middle Cambrian age, and below black Ordovician slate. The ores are generally in jasperoid and are surrounded by a shell of crystalline dolomite. Outside of the dolomite is a shell of coarse-grained calcite that in places was deposited along solution channels long distances from known ore bodies. Jasperoid, crystalline dolomite, and, to a less extent, coarse-grained calcite are therefore favorable but not infallible signs of the presence of ore nearby. The Metaline limestone was dolomitized regionally before the ore was introduced, and this early dolomitization is independent of the ore.

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* Published by permission of the Director, Geological Survey, United States Department of the Interior.

INTRODUCTION.

THE practical application of geology to mining in the Metaline district requires a consideration of the geologic structure and especially rock alteration. The purpose of the present paper is to discuss these topics, to point out their significance as guides to ore bodies, and thereby to assist the prospectors and miners in the region. Those interested in the more general geologic features of the district from a scientific viewpoint are referred to the final report, now in preparation.

LOCATION AND HISTORY OF MINING.

The Metaline district is in the valley of the Pend Oreille river (Clark Fork), Washington (Fig. 1). It may be reached by

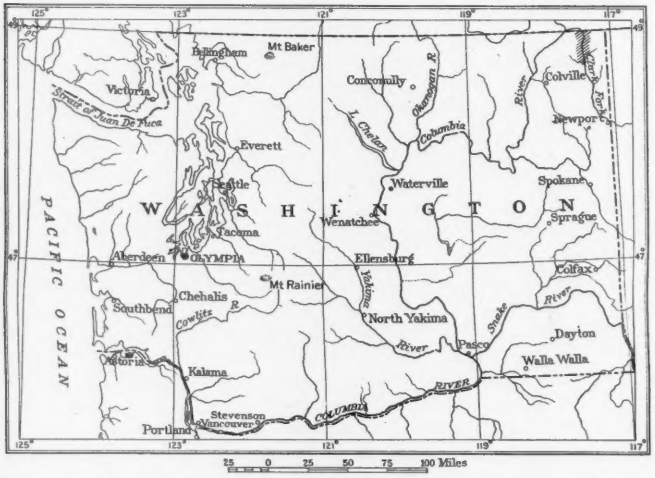


FIG. 1. Index map of Washington. Shaded area in the northeastern corner is the Metaline district.

paved highway from Spokane or by railroad from Newport. The lead-zinc deposits in the region have been known for many years. Bethune in 1891 reported that the name Metaline was used be-

cause of the large quantity of galena and sphalerite exposed in the river valley.[1] In 1909 and 1910 Bancroft made a hasty reconnaissance through the district,[2] and Jenkins described the condition of the mining properties in 1924.[3]

Many attempts to develop commercial ore have been made, but all early ones failed, partly because the ore was base and the content of lead and zinc as well as gold and silver low and partly because of the inaccessibility of the region. In 1928 the Pend Oreille Mining Co. drilled into a body of high-grade sphalerite-galena ore, which has since been partly developed and the limits greatly extended.[4] This company completed a new power plant on the Pend Oreille river in 1937 [5] and at the same time increased the mill capacity to about 600 tons daily. The other principal operator, the Metaline Mining and Leasing Co., a subsidiary of the American Zinc, Lead, & Smelting Co., drove a 4,800 foot adit in 1936 and 1937 in order to develop an ore body previously indicated by diamond drilling.[6] Mining and milling were begun late in 1937 but were suspended April 1, 1938, because of unfavorable economic conditions. Although these two companies are the largest producers in the district, numerous efforts are being made by other parties to develop additional ore.

The total production of the district from 1915 to 1936 inclusive is about 40,801,345 pounds of zinc, 11,339,131 pounds of lead, and a little silver and copper, valued at a total of $2,472,924. During 1936 the value of the production was $513,057, and with

[1] Bethune, G. A.: Mines and minerals of Washington. State Geologist, 1st Ann. Rept.: 82–83, 1891.

[2] Bancroft, H.: Lead and zinc deposits in the Metaline mining district, northeastern Washington. U. S. Geol. Surv., Bull. 470: 188–200, 1911. Ore deposits of northeastern Washington. U. S. Geol. Surv., Bull. 550: 40–51, 1914.

[3] Jenkins, O. P.: Lead deposits of Pend Oreille and Stevens Counties, Washington. Wash. Div. Geol., State Dept. Conservation and Development, Bull. 31, 1924.

[4] Larsen, L. P.: The Metaline lead-zinc district. Ariz. Min. Jour., June 15: 5–6, 1932.

[5] Lambly, C. A. R.: Pend Oreille solves power problem. Eng. and Min. Jour., Mar.: 40–42, 1938.

[6] Hayes, H. I.: Zinc company drives 2,000 feet at Metaline. Northwest Mining, Dec. 17: 1–4, 1936.

favorable economic conditions production probably will be maintained or increased.[7]

ACKNOWLEDGMENTS.

The field work upon which this paper is based was part of the geologic study of the Metaline quadrangle by the writer during nine months in the field seasons of 1936 and 1937. It is a pleasure to acknowledge the generous cooperation of the people in the district. Unhampered access to the underground workings and permission to study the thousands of feet of diamond-drill cores accumulated by the mining companies during the past 10 years have been of great value. The paper owes much to the untiring efforts and stimulating ideas of the writer's field assistants, G. R. Gibson in 1936 and R. S. Cannon, Jr., in 1937. The critical reading of this manuscript by J. S. Vhay, M. I. Goldman, J. T. Pardee, and A. C. Spencer is also appreciated.

GENERAL GEOLOGY.

A detailed presentation of the entire stratigraphic section in the Pend Oreille Valley is beyond the scope of this paper and will be given in the forthcoming report on the Metaline quadrangle.[8] The formations are given below. This table includes for comparison the strata described by Daly[9] and Walker[10] in the adjoining Salmo map-area north of Metaline.

The Monk formation and the lower part of the Gypsy quartzite are tentatively considered Cambrian (?) in age. Fragments of trilobites were found near the top of the Gypsy quartzite and are reported by Josiah Bridge to be of Cambrian age. Two collections of fossils, mostly trilobites, from thin-bedded limestone

[7] Production figures compiled by C. N. Gerry. U. S. Mineral Resources of the United States, 1915–32, and Minerals Yearbook, 1932–1936.

[8] Park, C. F., Jr., and Cannon, R. S., Jr.: Geology and ore deposits of the Metaline quadrangle, Washington. U. S. Geol. Surv., Rep. (in preparation).

[9] Daly, R. A.: Geology of the North American Cordillera at the forty-ninth parallel. Canada Geol. Surv. Mem. 38: 147–159, 271–277, 1912.

[10] Walker, J. F.: Geology and mineral deposits of the Salmo map-area, British Columbia. Canada Geol. Surv. Mem. 172: 2–10, 1934.

near the base of the Metaline limestone are reported by Bridge to be of Middle Cambrian age. Much of the black Ledbetter slate contains Ordovician graptolites and one collection of Devonian (?) fossils, mostly brachiopods, was made from a sandy dolomitic limestone west of Z Canyon.

STRATIGRAPHIC COLUMN IN THE METALINE DISTRICT, WASH.

This paper		Daly, 1912		Walker, 1934	
Limestone 700′	Devonian (?)	Pend Oreille group	Upper Paleozoic	Pend Oreille group	Windermere, late pre-Cambrian
Ledbetter slate 2,500′	Ordovician				
Metaline limestone 3,000′	Middle Cambrian				
Maitlen phyllite 5,000′+	Cambrian	Lone Star phyllite 2,000′+	Cambrian		
		Beehive formation 7,000′		Reno formation 3,500′	
Gypsy quartzite 5,300′–8,500′		Ripple quartzite 1,650′		Quartzite Range formation 4,400′	
		Dewdney formation 2,000′		Three Sisters series 5,400′	
		Wolf grits 2,900′			
Monk formation 3,800′+	Cambrian (?)	Monk formation 5,500′	Beltian	Horsethief Creek series 4,200′–	

The distribution of the formations in the Pend Oreille Valley is shown in Fig. 2. The sedimentary beds trend in general N. 10°–45° E. and dip either east or west. They are cut off to the south by the Kaniksu batholith, which is predominantly quartz monzonite, similar in composition and texture to the Nelson batholith to the north and the Idaho batholith to the southeast.

The rocks that border the Pend Oreille Valley were closely compressed, whereas those in the valley were more openly folded and intricately faulted. The dominant structural feature of the region is the Flume Creek–Russian Creek fault, which extends northward from the vicinity of Ione to about half a mile south of the Canadian border, where it swings abruptly westward (Fig. 2). This fault dips steeply, is normal, and the east side is downthrown, but the evidence will not be discussed here. The maxi-

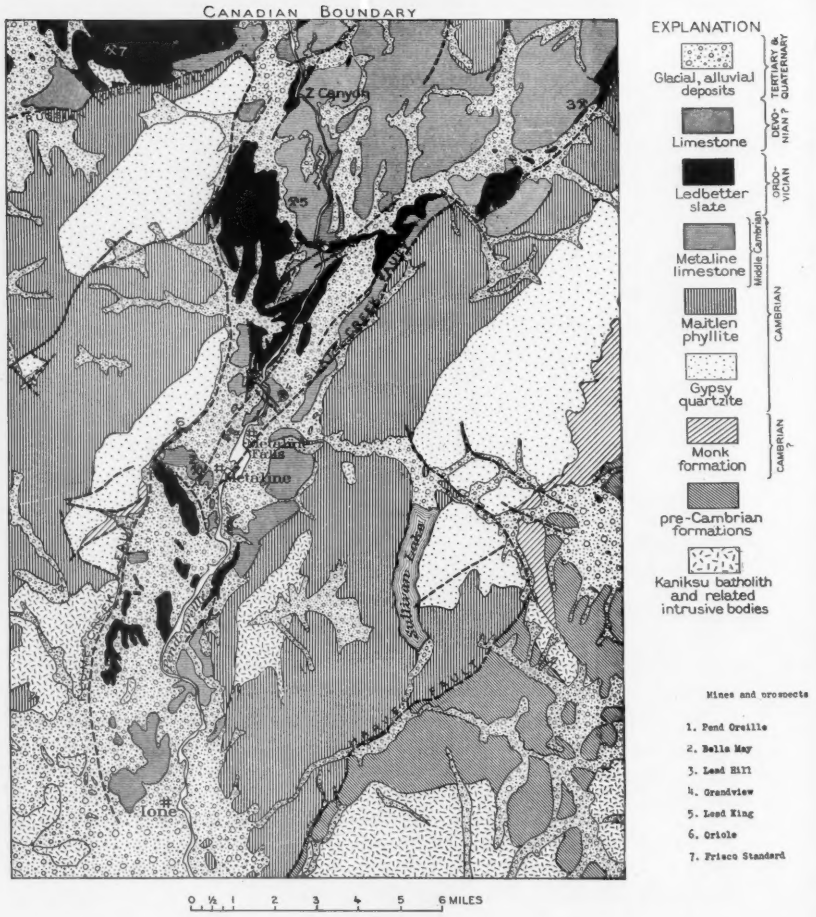


FIG. 2. Generalized geologic map of Metaline district, Northeastern Washington.

mum displacement on the fault is at least 12,000 feet. The eastern side of the Pend Oreille Valley is bordered by two large faults, the Slate Creek fault and the Harvey fault (Fig. 2), each of which is normal and has the west side downthrown. The Pend Oreille Valley is therefore a fault block, depressed relative to the rocks on each side. The structure of this depressed block is exceedingly complex, as the brittle limestones and incompetent slates and phyllites are greatly brecciated, faulted, and distorted. The difficulties of deciphering this complex structure are increased by the widespread, thick mantle of glacial and alluvial debris and by the dense cover of brush and trees. In Fig. 2, some of the generalized structural features of the valley block are shown, but the evidence for these features and their interpretation are too involved to be discussed here.

With the exception of a few replacement veins, such as that at the Oriole mine, the known zinc-lead deposits of the district are irregular replacement bodies in the Metaline limestone or exceptionally in other carbonate beds. They are mostly in the downfaulted block of the Pend Oreille Valley. The replacement ores so far developed are largely in the upper part of the limestone, commonly less than 500 feet below the Ledbetter slate, and are richer in the more faulted and brecciated areas. The increase of brecciation in and near the ore bodies and the numerous stylolites in the limestones below the ores suggest slumping due to solution or possibly mineralization stoping as defined by Locke.[11] The brecciation is, however, too widespread to be caused entirely by such a process. Many of the fragments are angular and show relatively little displacement or rotation. Much of the rock is classed as a crush breccia, or a crackle or mosaic breccia as the words are used by Norton.[12]

The contact between the Ledbetter slate and the underlying carbonate rock is of particular interest in the study of the alteration products, which are abundant in the beds just below the slate.

11 Locke, A.: The formation of certain ore bodies by mineralization stoping. ECON. GEOL., 21: 431–453, 1926.

12 Norton, W. H.: A classification of breccias. Jour. Geol., 25: 161, 188–189, 1925.

This contact is everywhere sharp, and the beds, where they lie in normal positions, appear to be conformable. Throughout the district the slate lies at probably the same horizon. This statement is based on general stratigraphic study and on the presence of a cherty zone, 450 feet thick, the top of which is about 150 feet below the slate. The abundant chert is in ellipsoidal nodules rarely more than 2 inches in greatest dimension and commonly an inch or less. Many of the nodules have hollow centers crossed by thin silica septa. The cherty horizon appears to be a distinct stratigraphic unit, and the depth below the slate is nearly constant. This fact is considered as evidence against the existence of an unconformity at the top of the Metaline limestone.

ROCK ALTERATION.

Dolomite.

Although some of the carbonate rocks in the Metaline district are nearly pure limestone and others are nearly pure dolomite, most of them are intermediate dolomitic limestones. Two types of dolomite are recognized: bedded deposits and crystalline dolomite not bedded. In places the two types cannot be clearly separated, although in general their differences are distinct.

Bedded Deposits.

Composition.—The magnesium content of certain beds is nearly constant over areas of a few square miles, and bedding planes separate layers of different composition. The sharp contacts between rocks of different composition do not, however, everywhere conform to bedding surfaces, and in places these contacts crosscut the bedding at high angles. Such a relationship is indicated near the base of the Metaline limestone in the middle Lehigh quarry east of Metaline Falls, where a wedge of limestone was mined for use in the manufacture of cement. This wedge was surrounded by dolomitic limestone and, so far as could be determined in the open quarry, no faulting was involved. The stratigraphic evidence indicates that certain beds are dolomites

in some places and are either dolomitic limestones or high-calcium limestones elsewhere. The beds just below the Ledbetter slate have this variable nature, but it has not been possible to follow single beds and obtain chemical data showing changes in composition along the strike.

The strata below the Ledbetter slate are particularly accessible in and near the Pend Oreille mine. At this mine no relationships could be established between the magnesium content and the contact of carbonate rock with slate. Layers of dolomitic limestone cannot be correlated and appear to crosscut the bedding. Much of the limestone is pure enough to effervesce freely with very dilute (1:15) cold hydrochloric acid. At Z Canyon and at Lead Hill the rock below the slate is a fine-grained, cream-colored dolomite that contains almost no calcite. Cores obtained by drilling at the Bella May, Grandview, Lead King, and several other properties furnish additional data as to the irregular distribution of the magnesium in the carbonate beds just below the slate.

Fig. 3 is a series of graphs plotted from analyses of drill cores below the Ledbetter slate. In these samples no effort was made to separate the crystalline dolomite that is not bedded. For this reason the analyses do not accurately represent the composition of bedded dolomites, but the crystalline dolomite is in small quantities except where the insoluble portion is high. The graphs show clearly that the composition of the beds at definite horizons below the contact with the Ledbetter slate is not uniform. Without discussing here the genetic implications involved, it may be pointed out that the ore bodies are found in zones that show large percentages of insoluble constituents and are bordered by large amounts of dolomite or coarse calcite. A striking agreement in the distribution of magnesium, iron, and manganese is also brought out by the analyses, but for the sake of simplicity iron and manganese are not plotted on the graphs. The two elements together generally amount to less than 2 per cent.

Texture, Color and Structure.—Many of the dolomites and dolomitic limestones are so fine-grained that cleavage surfaces of grains are not visible in hand specimens. Other beds are re-

crystallized and cleavage surfaces one-eighth to one-fourth inch across are developed. All the dolomites studied contain small crystal-lined vugs, generally less than one-fourth inch in diameter, although a few are larger.

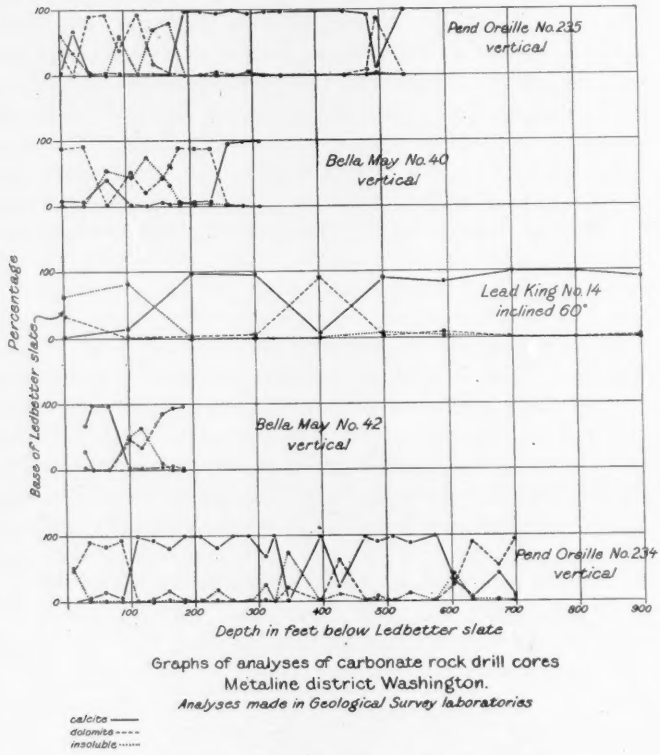


FIG. 3. Graphs of analyses of drill cores.

The colors range from light cream through light gray to dark gray and black. During recrystallization the organic coloring matter has been expelled, and the coarser crystalline beds are therefore lighter. In several places the organic material has ac-

cumulated as small rounded globules, less than one-half inch in diameter that have the composition of anthracite.[13] Most of the globules fill vugs that are lined with dolomite or calcite crystals, although a few are lined with quartz.

Alternating layers of black and cream-colored or light-gray dolomite are common in the lower part of the Metaline limestone. Most of these layers are 4 feet or less thick, but some attain 10 feet. Most of them coincide with the bedding but some cut across it. Also irregular patches of the black dolomite as much as several feet across are isolated in the lighter material. Spots of white crystalline dolomite about one-half inch or less in greatest dimension are scattered irregularly through the dark layers and give them a characteristic speckled appearance. Samples of the light and dark layers collected about 1 foot apart in the same bed were analyzed by R. C. Wells. The two analyses are almost identical and agree closely with the composition of dolomite. A small but discernible amount of carbonaceous material was found in the dark layer. In thin sections the black layers have a smoky appearance and are finer grained than the lighter ones.

Fig. 4 illustrates a somewhat unusual type of banded dolomite that is appropriately called "zebra rock" by the miners. The term "zebra rock" has, however, been applied to other banded rocks[14] and is used here only for convenience. The black and white layers are generally less than 0.5 inch thick and are commonly 0.2 inch or less. The compositions of the two are identical except for a little carbonaceous material in the darker parts and a slightly coarser texture in the light bands. In several places the "zebra" banding appears to be related to fracturing and shearing, and the bands fray out away from the more sheared areas. The suggestion is here offered that the "zebra" banding

[13] Hendricks, T. A.: Recently adopted standards of classification of coals by rank and grade. ECON. GEOL., 33: 136–142, 1938. Fixed carbon determined by Taisia Stadnichenko.

[14] Hobson, R. A.: "Zebra rock" from the east Kimberly. Jour. Royal Soc. West Australia, 16: pp. 57–70, 1930. Crawford, R. D., and Gibson, R.: Geology and ore deposits of the Red Cliff district, Colo. Colo. Geol. Surv., Bull. 30: 36, 1925.

is caused by recrystallization of gray or black dolomite along closely spaced surfaces. The trends of these surfaces are determined by shear planes, which in places follow bedding or other planes. A tendency has been noticed in the district to consider "zebra" banding coincident with bedding. Certainly in some places the banding cuts the bedding at high angles, and where the two features coincide it is probably caused by movement along the bedding.

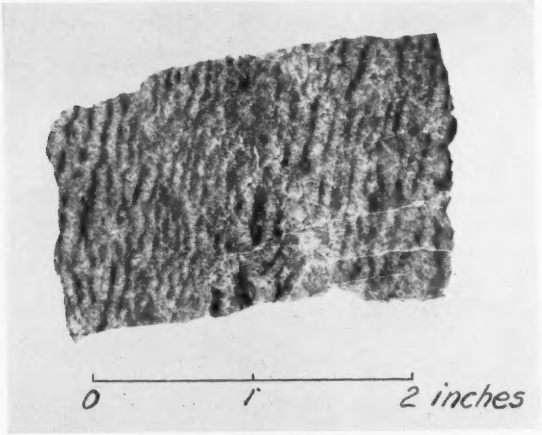


FIG. 4. "Zebra" dolomite, Granview mine.

Crystalline Dolomite not Bedded.

Crystalline dolomite is found near and in ore deposits and bodies of jasperoid that are associated with the ore minerals, and along faults and in breccia zones. It is particularly abundant in the rocks just below the Ledbetter slate, where it is independent of bedding and tends to obliterate bedding and other sedimentary structures. The quantity of non-bedded crystalline dolomite is insignificant as compared to that of the bedded type.

Composition.—The crystalline dolomite is nearly pure calcium-magnesium carbonate. Small amounts of iron and manganese,

similar to those in the bedded dolomites, were detected in at least some of the material, but the analytical data on the distribution of these elements in the crystalline dolomites are insufficient to permit conclusions. In places the contacts between the bedded and crystalline dolomites are sharp, but in other places the two types seem to grade into each other.

Texture and Structure.—Grain boundaries and cleavage surfaces are readily recognized in the crystalline dolomites. Most of the individual grains average about 0.1 to 0.2 inch across, although a few are coarser and a few finer. Much of the crystalline dolomite is vuggy, and the vugs are lined with well-formed dolomite or calcite crystals. The color of the dolomite ranges through creams and grays and is seldom uniform. Irregular spots and bands, probably caused by slight differences in organic content, are commonly seen and appear, at least in places, to be caused by the preservation of corroded and largely recrystallized remnants of bedded dolomite.

A concentrically banded rock that is of particular interest in the study of the alteration products is illustrated in Fig. 5. This rock is not abundant but has been noted at several properties, especially those near Z Canyon. It resembles some of the zinc ores from the Southern Appalachian deposits [15] and from Upper Silesia.[16] Currier believes the structure is partly cavity filling and partly replacement of a breccia in which the sharp corners were most rapidly attacked. Krusch attributes the structure in the Upper Silesian ores to rhythmic precipitation from a colloidal state.[17] It would appear that concentric banding might result from either or both of these processes. No conclusive evidence in support of either idea was found at Metaline.

[15] Currier, L. W.: Personal communication, March 1938. Zinc and lead region of southwestern Virginia. Virginia Geol. Surv., Bull. 43, pls. 24, 25, and 26, 1935.

[16] Stappenbeck, R.: Ausbildung und Ursprung der oberschlesischen Bleizinkerzlagerstätten. Preuss. geol. Landesanstalt Archiv für Lagerstättenforschung, 41: 79–85, 1928.

[17] Krusch, P.: Uber kolloidal Vorgange bei der Entstehung der oberschlesischen Zink-Bleierzlagerstättan. Zeitschr. Deutschen Geol., 81: 169–170, 1929.

FIG. 5. Concentrically banded rock from Z Canyon mine. Light-gray material is mostly crystalline dolomite with some silica and pyrite grains near the centers of the nodules. Black material is sphalerite with galena along the outside borders. White is calcite.

Jasperoid.

Jasperoid or silicified carbonate rock is widespread in the Pend Oreille Valley. It is particularly abundant at Lead Hill and in the Pend Oreille mine but is noticeable near or in most ore bodies. The silicified rock resists weathering and generally stands above the surrounding dolomite and calcite.

The jasperoid is a very fine grained dense gray or black rock that uniformly preserves the texture and structure of the replaced rock. Fig. 6 is a photograph of a polished slab of silicified and mineralized breccia from the Pend Oreille mine.

Up to the present, it seems that in this area, the zinc ores are most abundant and richest in the jasperoid. Jasperoid commonly accompanies zinc ores in many mining districts, but the ores are generally near rather than in the silicified rock.[18]

Irving recognized two types of silicification of carbonate rocks connected with the formation of ore deposits. In one the silica content gradually increases from the carbonate rock to the jasperoid and in the other silicification advanced in waves and the contacts are sharp.[19] The silicification in the Metaline district is of the first type; the silica extends into the carbonate rock in minute veinlets and scattered doubly terminated crystals and the boundaries are not sharp. Small vugs that contain quartz crystals which seem to merge with the jasperoid are common and are particularly well exposed in the Pend Oreille mine.

The close association of the jasperoid and the ore and the relationships between them are interpreted to mean that the two products were derived from the same solutions, probably hydrothermal.

[18] Gilluly, James: Geology and ore deposits of the Stockton and Fairfield quadrangles, Utah. U. S. Geol. Surv., Prof. Paper 173: 97–101, 1932. Emmons, S. F., Irving, J. D., and Loughlin, G. F.: Geology and ore deposits of the Leadville mining district, Colo. U. S. Geol. Surv., Prof. Paper 148: 217–219, 1927. McKnight, E. T.: Zinc and lead deposits of northern Arkansas. U. S. Geol. Surv. Bull. 853: 111–112, 133–136, 1935. Loughlin, G. F., and Behre, C. H., Jr.: Ore deposits of the Western States (Lindgren volume). A. I. M. E., pp. 39–40, 1933.

[19] Irving, J. D.: Some features of replacement ore bodies and the criteria by means of which they may be recognized. Can. Min. Inst. Jour., 14: 422, 1911; Econ. Geol., 6: 556–558, 1911.

FIG. 6. Silicified and mineralized breccia from the Pend Oreille mine. Light-gray material is mostly dolomite with a little translucent quartz. Dark-gray material is jasperoid and ore minerals. Veinlet along lower edge of specimen contains sphalerite in carbonates.

The spherulitic structure shown in two of the larger silicified breccia fragments in Fig. 6 resembles the structures at Tintic[20] and at Mercur[21] that have been interpreted to indicate an intro-

[20] Lindgren, W., and Loughlin, G. F.: Geology and ore deposits of the Tintic mining district, Utah. U. S. Geol. Surv. Prof. Paper 107: 154–158, 1919.

[21] Gilluly, J.: Geology and ore deposits of the Stockton and Fairfield quadrangles, Utah. U. S. Geol. Surv., Prof. Paper 173: 97–101, 1932.

duction of silica in the colloidal state. It is difficult to understand why colloidal solutions, or true solutions either, should deposit these small spheroidal nodules by replacing a massive carbonate rock and yet preserve the outline of the replaced fragments, unless spheroids were present in the original rock. Spheroids of this type were seen only in the jasperoid.

Spheroidal nodules of known colloidal origin are usually considered to form as gels in open spaces. Those who criticize the theory of formation of silica as a gel note the absence of dehydration or shrinkage cracks in the resulting quartz. The criticism may be voided if the Wiegner effect is active. This effect is defined by Liesegang as follows: "When a polydispersoid sol coagulates, submicrons will act as coagulation nuclei for amicrons. Flowing water can then bring highly dispersed minerals into contact with larger mineral particles and form shell-like layers."[22] This means that when a colloidal solution that contains several types of suspended particles coagulates, the larger particles or submicrons act as coagulation nuclei for smaller particles or amicrons. (Submicron is a particle visible under the ultramicroscope and amicron is a particle not visible under any microscope.) So far as known, this effect is active in small spaces and does not require more than very thin layers of gel at any one time. It may help to explain the origin of such spheroids as shown in Fig. 6.

In the new Bella May tunnel and at Lead Hill light-gray, fine-grained silica has been extensively introduced into the dolomitic limestone. This silica resembles the darker jasperoid except in color, and the relations between the two types of silica are unknown. The two may have similar origins or the light-gray silica may possibly be supergene.

Coarse-Grained Calcite.

Translucent white calcite with cleavage surfaces 6 inches or more across is commonly found near and in known ore deposits, along faults, and in irregular areas remote from known ore.

[22] Liesegang, R. E.: Colloid chemistry and geology. Colloid Chemistry, vol. 3, ed. by Jerome Alexander, p. 253, 1931.

Where the road to the Pend Oreille mine crosses Flume Creek Gorge massive cliffs of coarse calcite are well exposed.

Analyses of the calcite show it to be practically pure calcium carbonate. Both pre-ore and post-ore calcite are recognized, but physically and chemically they seem to be identical. In the Pend Oreille mine galena commonly replaces calcite along cleavage cracks, but in other places (Fig. 5) calcite-filled fractures cut galena. This contradictory evidence may be interpreted to indicate two ages of calcite, two ages of galena, or one period of overlapping deposition. Similarly the relationships of calcite to both nonbedded crystalline dolomite and quartz are contradictory.

DEVELOPMENT OF THE ALTERATION PRODUCTS.

The earliest alteration of the carbonate rocks appears to have been dolomitization of the original limestone without complete destruction of the bedding. The widespread but erratic distribution of the magnesium, both vertically and laterally through the limestone beds, indicates that the bedded type of dolomite was formed from underground, probably ascending solutions. It makes improbable an origin by direct precipitation from sea water or from groundwater of meteoric origin. If the bedded dolomites are formed by interchange from circulating underground solutions the alteration should be more complete near paths of easy access, which means, in general, that dolomitization is related to structural features. If accomplished by underground waters, the controlling structural features, probably none too conspicuous at any time, are greatly obscured by post-dolomitization deformation.

It cannot be said that brecciation is limited to the dolomitized beds. Some of the mineralized breccias in the Pend Oreille mine contain limestone fragments. On the other hand, the gently tilted but otherwise slightly deformed beds south and east of Z Canyon are almost uniformly dolomites and dolomitic limestones.

Bedded dolomites and dolomitic limestones have been faulted and brecciated in many places. Some of the breccias are un-

cemented, and others are cemented by silica and calcite. Dolomite beds are dragged along faults, and fragments of dolomite and limestone are mixed in the gouge. Dolomitization was probably accomplished before introduction of the ore-bearing solutions and it may have taken place early in the structural history.

Hewett, in a discussion of the origin of dolomite, points out that magnesium is freed during silicification of dolomite. This liberated magnesium could then alter to dolomite any limestone through which the transporting solution later passed.[23]

Knopf described coarse white calcite similar to that at Metaline, around the margins of many replacement deposits in limestone at Pioche, Nevada. He considers that the calcite results from the recrystallization of aphanitic limestone and offers the explanation that the "spent or depleted ore-forming solutions, though no longer able to replace the limestone that surrounds the ore bodies by ore, were able to recrystallize it." The alternative explanation offered is that the "calcite was the most advanced member of the vanguard in front of the growing ore body."[24]

A combination of the ideas expressed by Hewett and Knopf offers a reasonable explanation of the alteration at Metaline. Most probably the large bodies of jasperoid were deposited by hot solutions, that also transported the sulphides. Large quantities of magnesium and calcium carbonates were liberated when bedded dolomites and dolomitic limestones were replaced by jasperoid and ore. These liberated carbonates were moved along solution channels away from the sphere of silicification and were redeposited nearby in more favorable places. In general the solutions that resulted from the dissolving of dolomitic limestone contained calcium carbonate in excess of the amount required to form dolomite with the available magnesium. The result has been the deposition of crosscutting bodies of crystalline dolomite and coarse-grained calcite. Additional calcite was also liberated during the deposition of crystalline dolomite in dolomitic lime-

[23] Hewett, D. F.: Dolomitization and ore deposition. ECON. GEOL., 23: 859, 1928.

[24] Westgate, L. G., and Knopf, A.: Geology and ore deposits of the Pioche district, Nevada. U. S. Geol. Surv., Prof. Paper 171: 49–50, 52, 1932.

stone. The quantity and distribution of the crystalline dolomite and the coarse-grained calcite seems to be adequately accounted for by this interpretation, which also explains the complicated paragenesis of the silica, sulphides, dolomite and calcite. That some recrystallization has taken place with a minimum of transportation is indicated by the local gradation of the crosscutting crystalline dolomite into bedded fine-grained dolomite.

ECONOMIC FACTORS.

A few suggestions of possible value in prospecting for additional ore are brought out by this investigation. Assuming that the ideas outlined above are correct, the presence of jasperoid, crystalline cross-cutting masses of dolomite, and coarse-grained calcite are favorable but not infallible signs of the presence of ore nearby. Areas in which these alteration products are found are at least worthy of additional study and possibly exploration.

The distribution of ore and its associated alteration products is closely related to the prominent structural features of the region. Most ore bodies are in the hangingwalls of the Flume Creek-Russian Creek fault and the Slate Creek fault, but a few, such as that at the Oriole mine, are in the footwalls. The ore bodies are generally less than a mile from the major faults and are associated with breccia zones and minor fractures. Several ore bodies, such as those near Z Canyon and the mouth of Slate Creek, are localized in and near other structural features, particularly faults and breccia zones.

Prescott made the interesting statement in 1926 that "The first favorable limestone encountered by the ascending mineralizer is often by far the most productive."[25] In the Metaline district the known ores are largely in the easily fractured Metaline limestones, generally less than 500 feet below the overlying Ledbetter slate. These ores are underlain by about 2,500 feet of carbonate rock, interbedded near the base with shales. No obvious

[25] Prescott, Basil: The underlying principles of the limestone replacement deposits of the Mexican province. Eng. and Min. Jour., 122: 247, 1926.

reason is known why some of the lower horizons should not be ore bearing, and some may prove worthy of exploration. The favorable lower carbonate beds in the known ore-bearing areas are, however, generally 1,000 feet or more deep, and development of them will probably be a slow and costly process.

It is not a purpose of this paper to discuss the theoretical considerations why dolomite is or is not more favorable for ore deposition than limestone. The field observations agree closely with those of Vanderwilt in Colorado [26] and of Haywood and Triplett in northern Mexico,[27] where regional dolomitization preceded ore deposition and little or no magnesia was added by the ore-bearing solutions. The ore is generally in jasperoid that has replaced dolomite or dolomitic limestone, but in places it is in limestone and is there commonly surrounded by a shell of crystalline dolomite and coarse-grained calcite.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
June 24, 1938.

[26] Vanderwilt, J. W.: Revision of structure and stratigraphy of the Aspen district, Colorado, and its bearing on the ore deposits. ECON. GEOL., 25: 238–241, 1935.

[27] Haywood, M. W., and Triplett, W. H.: Occurrence of lead-zinc ores in dolomitic limestones in northern Mexico. A. I. M. E., Tech. Pub. 442, 1931.

BAUXITE DEPOSITS AT GÁNT, HUNGARY.

QUENTIN D. SINGEWALD.

ABSTRACT.

Near Gánt, in Hungary, is located one of the world's largest reserves of readily accessible bauxite. The deposits, although discovered in 1915, have only recently been extensively exploited. Present workings consist of two open pits, in each of which a remarkably continuous layer of bauxite ranges from 15 m. to 30 m. in thickness. The bauxite, thought to be of Lower Cretaceous age, overlies an uneven surface of Triassic dolomite, and is in turn overlain in part by Tertiary strata, in part merely by unconsolidated materials. Associated faults have been important in localizing areas preserved from recent erosion.

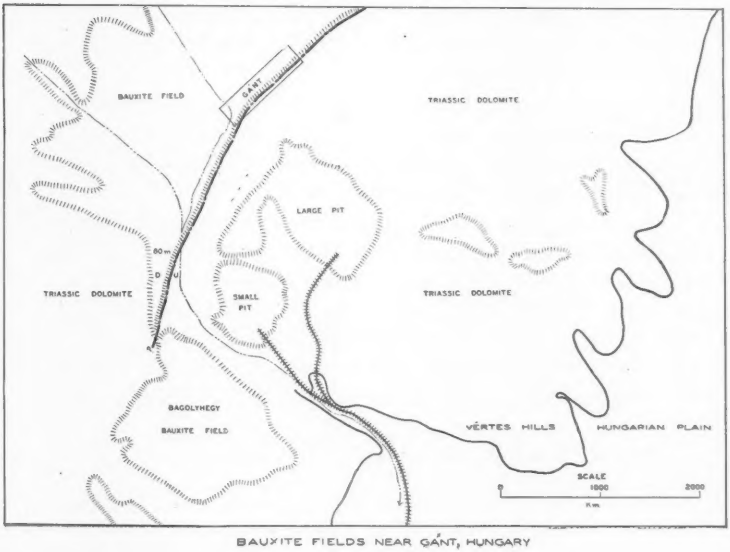
INTRODUCTION.

A SPECTACULAR recent achievement in metal mining in central Europe has been the bauxite industry of Hungary, whose production rose from a small figure prior to 1932 to nearly half a million tons in 1937. Thus, Hungary now approaches France —for some years the world's outstanding leader—in production and may in the near future even surpass France.

Although bauxite occurs in workable quantities at several localities in Hungary virtually the entire present output comes from Gánt (Fig. 1), approximately 70 km. west-southwest of Budapest, on the southern border of the Vértes Hills. In spite of the commercial importance of these deposits, descriptions of their geologic occurrence are limited to a few papers, mostly dealing with special features, published prior to the recent large development and difficult of access to most geologists. Consequently, the present paper combines published observations with new information obtained during a visit made in October, 1937. The writer is deeply grateful to Aluminiumérc, Bánya és Ipar R. T., Budapest, particularly to Mr. Josef Iványi, director, and Mr. Vilmos Nemes, engineer, for data and many courtesies and to Mr. Iványi for reading this manuscript.

FIG. 1.

Present production is from two separated deposits worked by open pits, known locally as the "large" pit and the "small" pit (Fig. 2). Cars from the mine carry the ore 16 km. along narrow



BAUXITE FIELDS NEAR GÁNT, HUNGARY

FIG. 2.

gauge track to a loading station on the railroad at Bodajk. From there, the bulk of the ore is shipped to Germany.[1] The ore contains from 50–63 per cent Al_2O_3, 15–30 per cent Fe_2O_3, and 2–4 per cent SiO_2. Reserves proved by drilling are sufficient to meet any probable demand for many years. The total reserves as estimated by the Hungarian Geological Survey are 120,000,000 tons.

REGIONAL GEOLOGY.

The regional geologic setting is rather simple. Northwest of a line extending from Budapest to Lake Balaton are several areas in which Triassic "hauptdolomit" projects through the surrounding Tertiary and Quaternary cover and forms low ranges of hills. To the southeast lie the Hungarian Plains. Within the Triassic areas occur scattered residual patches of younger rocks, mainly yet not entirely Eocene. Associated with them at many places in the central and southwestern ranges, the Vértes and Bakony (north of Lake Balaton) Hills, respectively, is bauxite. Igneous rocks that have no apparent genetic connection with the bauxite crop out north of Budapest, northwest of Lake Balaton, and near Székesfehervár.

It is interesting to note that Taeger[2] first mapped the bauxite as Tertiary "laterite and terra rossa." Later, an analysis made during a geological investigation for coal, by Szontagh,[3] proved the "terra rossa" to be aluminum ore.

Almost everywhere the bauxite rests on Triassic dolomite, yet locally it has been found above marine Jurassic strata. The beds where not eroded immediately above the bauxite were found to be middle Eocene in all the deposits first examined, and so the bauxite was originally regarded as having formed either between the Cretaceous and Tertiary periods or during the early Tertiary, as indicated in the general description by Roth v. Telegd.[4] More

[1] See U. S. Bur. Mines, Foreign Minerals Quar., vol. 1, p. 82, 1938.

[2] Taeger, H.: Die geologischen Verhältnisse des Vértesgebirges. Jahresber. d. k. Ung. Geol. Reichsanst., Vol. XVII, 1909.

[3] Szontagh, Th. v.: Geologische Aufnahme zwischen Biharrosa, Bihardobrosd, und Vércsorog. Jahresber. d. k. Ung. Geol. Reichsanst., 1915.

[4] Telegd, K. Roth v.: Die bauxitlager des Transdanubischen Mittelgebirges. Földtani Szemle (Ung. Rund. f. Geol. u. Pal.), vol. 1, 1927.

recently, however, bore holes have proved the bauxite at several localities to underlie Cretaceous beds; the fossil content of the latter, according to Vadász,[5] indicates an age not younger than Aptian. Moreover, marine strata as young as Barrémien, though not associated with bauxite, exist in the general region. Hence, Vadász concludes that bauxite could have formed only during the Lower Cretaceous, while the region was slowly emerging from the sea. Later weathering of the bauxite produced a red clay, moderately high in aluminum, that was redeposited and now exists locally at the base of the Eocene and that, according to Vadász, has been mistakingly correlated with the real bauxite.

LOCAL GEOLOGY AT GÁNT.

In addition to bauxite, the consolidated rocks in the immediate vicinity of Gánt are white, sugary-looking Triassic dolomites and Tertiary strata, chiefly marls and clays. On the southern outskirts of the town (Fig. 2) a fault trending northeast and having a throw of approximately 80 m. divides the district into a northern area in which the bauxite is too deep for profitable mining and a southern area containing the workable deposits. Eocene strata overlying the bauxite in the northern area are overlapped to the northeast by unconsolidated gravel. Not enough prospecting has been done to know whether bauxite is continuous under this entire area.

Southeast of the fault are a number of bauxite bodies separated by barren areas of dolomite. Their locations according to a geologic map originally published by Pobozsny[6] and later republished by Dittler[7] are indicated by Fig. 2. In places, the bauxite is overlain by Tertiary strata, elsewhere only by unconsolidated materials. The principal structural features seen in the three main deposits are depicted in Fig. 3. The upper surface of the Triassic dolomites, in general, slopes gently to the

[5] Vadász, Elemér: Das geologische Alter der Transdanubischen Bauxitbildung. Centralblatt f. Min., Geol., u. Pal., pp. 429–442, Abt. B., 1934.

[6] Pobozsny, J.: A Vértesheğyseg bauxit telepei. Földtani Szemle (Ung. Rundschau f. Geol. u. Pal.), vol. 1, 1928.

[7] Dittler, E.: Die Bauxitlagerstätte von Gánt in Westungarn. Berg—u. hüttenm. Jahrb., Leoben, vol. 78, pp. 46, 1930.

northeast, parallel to the bedding, but is cut by a series of northwest trending fold-faults, all with upthrow not exceeding 40 m. on the east. The result is a step-like series of surface or, locally, slightly buried ridges. Bauxite occurs mainly in depressions between the ridges (Fig. 3), yet in places has not been entirely eroded above them. Tertiary strata, which overlap the bauxite in the large pit, become increasingly thick to the northeast. It is probable, therefore, that another northwest trending fault, now concealed, forms the northeast boundary of the deposit.

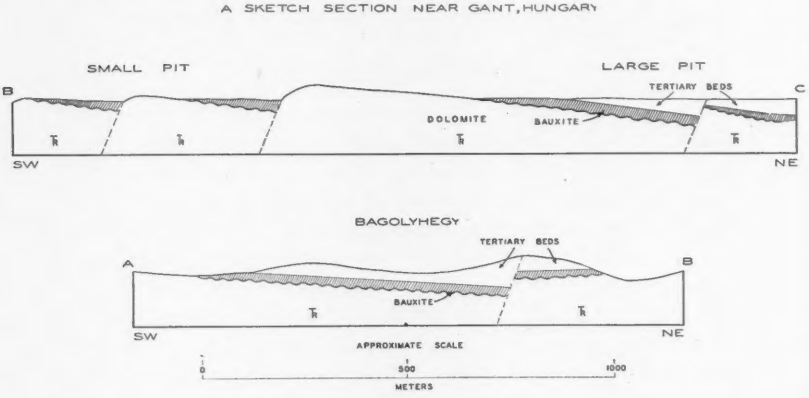


FIG. 3.

The upper surface of the dolomite series where covered by bauxite is exceedingly irregular in detail, preserving a karst-like topography whose maximum relief is 25 meters. Moreover, irregularly rounded boulders or masses of dolomite, up to several meters thick, are common within the lower part of the bauxite itself. These detached masses invariably are permeated with some manganese stain. The upper contact of the bauxite where overlain by Tertiary strata, on the other hand, is remarkably smooth.

The bauxite is prevailingly medium red, yet ranges from deep red to pale yellow. Although the upper part tends in general to be more pisolitic than the lower, there is really no uniform dis-

tribution of textures. Massive bauxite grades laterally into pisolitic, and the pisolitic variety in places has a conglomeratic or brecciated aspect. Moreover, the quantity of pisolites differs greatly within short distances. It is safe to say, however, that the bulk of the bauxite contains at least a few pisolites. Locally, a rude stratification is apparent in the upper part. In general, the upper part of the deposit has slightly higher quality than the lower. According to Dittler, who made microscopic and X-ray analyses of the mineralogy, the bauxite is mainly a mixture of aluminum hydroxide, iron-oxide, and sub-crystalline böhmite ($nAl_2O_3.H_2O$).

In the small pit the bauxite is overlain by soil or by a thin layer, 1 m. thick, of limestone pebbles in a sandy clay matrix that in turn is overlain by "lœss" and then soil. As may be seen from Fig. 3, thick bauxite occurs in two bands separated by a dolomite ridge.

The bauxite worked in the large pit extends from its outcrop eastward beneath an increasingly thick cover of Tertiary strata to the easternmost fault shown in Fig. 3, is displaced upward by the fault, and then dips again eastward. It is interesting to note the abrupt change in thickness of bauxite across the fault; this suggests that movement was initiated on the fault before the Tertiary strata were deposited, for there is no evidence of important horizontal displacement that could account for the change in thickness. Overlying the bauxite is a 4 m. layer of blue clay that is exceedingly sticky when wet. The clay is succeeded by 1 m. of fossiliferous limestone, then a series of alternating marls, sandy clays, and thin, impure lignite seams.

Where now being mined the bauxite ranges from 15 to 30 m. thick. Variations in thickness are caused both by irregularities on the floor and by the effects of recent erosion. Nevertheless, the large extent of continuously thick bauxite in each pit is noteworthy.

Southwest of the "small" pit, and separated from it by a narrow valley, is a relatively large bauxite field not yet exploited. This field has been prospected, however, by means of an underground gallery nearly 100 m. long, many shafts, and numerous

drill holes. These indicate a continuous bauxite layer, interrupted only by the fault shown in Fig. 3. The bauxite ranges from 10–20 m. in thickness, but is overlain by Eocene strata ranging from 10–50 m. in thickness. In the remaining, small bauxite fields, some of which are shown by Fig. 2, in the Vértes Hills, the bauxite is decidedly thinner.

ORIGIN.

The irregular distribution of textures and, particularly, the large included masses of dolomite completely detached from the main underlying beds strongly suggest that the bulk of the bauxite formed essentially in situ. On the other hand, the upper part locally exhibits rude stratification and even contains what look like bauxite boulders; hence, toward the close of the formation period some of the material may have been reworked or, more probably, small quantities of bauxite may have been transported short distances from surrounding areas into main basins of accumulation. The chief influence of the faults that now delineate the ore-bodies apparently was to modify the effects of later erosion.

UNIVERSITY OF ROCHESTER,
ROCHESTER, N. Y.,
June 13, 1938.

SOME TITANIFEROUS MAGNETITES OF THE SAN GABRIEL MOUNTAINS, LOS ANGELES CO., CALIFORNIA.

W. W. MOORHOUSE.

ABSTRACT.

In the last twenty years investigators have cast doubt on the metallic oxides being among the first minerals to crystallize in a cooling magma, in the case of the oxide ores in basic and ultra-basic rocks. They have considered them to be "late magmatic," late-phase injections, and even hydrothermal.

Support to this interpretation is supplied by the microscopic study of some titaniferous magnetite ores occurring in a massive anorthosite body of variable facies, located in the San Gabriel Mountains, Los Angeles Co., California. These ores are thought to be deuteric (pneumotectic) in origin, for the following reasons: (1) They occur in an igneous rock type with which similar deposits are commonly associated, and therefore are not hydrothermal. (2) Their relationships, under the microscope, show that they are later than feldspar, pyroxene, apatite, mica, titanite, and in part, at least, later than hornblende, epidote and clinozoisite. (3) They are associated with deuteric phenomena, such as albitization and reaction rims and with late-forming minerals such as biotite and amphibole. (4) They are found in zones of granulation and alteration in the anorthosite.

Not only are titaniferous magnetites considered to be deuteric, but the suggestion is made that the ore comprising titaniferous magnetite, pyroxene and apatite, may represent a pegmatitic phase of the anorthosite. The relationship of these minerals to one another, and the association of the apatite in specimens of altered anorthosite, together with long-recognized features of certain basic igneous rocks, all support this hypothesis.

INTRODUCTION.

Ore deposits, especially of the oxide ores, in or associated with basic or ultra-basic igneous rocks were formerly considered to be the result of early crystallization and segregation in the magma. However, some twenty years ago, the work of Tolman and Rogers on the "Magmatic Sulphides" cast serious doubt on the Rosenbusch interpretation of the order of crystallization. Tolman and Rogers included in their group of "Magmatic Sul-

phides" ores that have been developed in the parent basic rock after consolidation, but commonly precede, in their formation, pegmatitic differentiates of the same igneous cycle. These sulphides succeed hornblende, which is formed by the magmatic alteration of pyroxene at a late stage in the consolidation of the igneous rock, but are followed by all other alteration minerals, that is, quartz and secondary silicates. They were designated "late magmatic" by the authors. Their investigations led Tolman and Rogers to the conclusion that magnetite and ilmenite ores are also formed at the late magmatic stage, and that other common accessory minerals may boast a similar origin.

In regard to certain of the iron-ore deposits in basic igneous rocks, Vogt[1] contributed another modification of the original theory. He believed that in some cases the ores separated as an immiscible liquid, to be later injected into solidified differentiates of the parent rock as a sort of diaschistic dike.

Modifying this concept, Osborne,[2] in his studies of titaniferous magnetite and ilmenite deposits of Quebec and New York, attributed their origin to "filter-pressing" of a differentiating magma with the consequent injection of an iron-rich segregate into other sections of the cooling rock. This theory necessarily is related to the "late magmatic" processes of Tolman and Rogers, since it requires the crystallization of the feldspathic constituents of the magma, with the separation of a "rest-magma" from which the iron ores and pyroxenes are separated after its final emplacement.

Gillson,[3] discussing the St. Urbain, Quebec, ilmenite deposits, takes a further step away from the older ideas concerning the origin of the oxide ores. He believes that they were deposited from gaseous or liquid solutions in the solid, although still warm anorthosite country rock. The basis for his interpretation lies

[1] Beyschlag, F. H. A., Vogt, J. H. L., Krusch, P.: The deposits of the useful minerals and rocks, tr. S. J. Truscott, p. 255. MacMillan, London, 1914–16.

[2] Osborne, F. F.: Certain magmatic titaniferous iron ores and their origin. ECON. GEOL., XXIII: 724, 895.

[3] Gillson, J. L.: Genesis of the ilmenite deposits of St. Urbain, Charlevoix County, Quebec. ECON. GEOL., XXVII: 554, 1932.

in the recognizable paragenesis and the notable relationship to structure which the deposits exhibit. The wide association of similar ores with this type of rock leads him to believe that the two are derived from the same magma.

Fisher [4] recognizes in chromite deposits all three origins, namely, pyrogenetic, late magmatic and hydrothermal. He is inclined to assign the greatest importance to the second group. It is highly improbable, at all events, that any one mode of origin will successfully account for all examples of oxide ores.

In this connection, the author presents evidence that the titaniferous magnetites of the San Gabriel Mountains, Los Angeles County, California, appear to be of "late magmatic," or, more correctly, deuteric origin. These conclusions are based on the microscopic investigation of material collected by Mr. Burt Beverley in the Upper Tujunga Canon in the area mentioned. The specimens are unusually fresh, and a study of the sections revealed such interesting relations that it was felt worthwhile to record them. Unfortunately no accurate geological examination was made in the vicinity of the deposits with this in mind, so that the conclusions drawn must depend almost entirely on microscopic evidence. To that extent they must be regarded as provisional.

GENERAL GEOLOGY.

According to Miller [5] the titaniferous magnetites occur in an anorthosite of variable facies, about eighteen miles in diameter. In addition to true labradorite rocks, it includes dioritic and, less commonly, gabbroic types. These generally occur in such form as to be interpreted by Miller as segregations, grading into the more typical anorthosite. However, in some cases, they appear to be definitely earlier in crystallization, being cut by the normal anorthosite.

Miller states that "Many definitely local, irregularly distributed portions of the dioritic and gabbroic facies of the anorthosite

[4] Fisher, L. W.: Origin of chromite deposits. ECON. GEOL., XXIV: 691, 1929.
[5] Miller, W. J.: Geology of the Western San Gabriel Mountains of California. Univ. of Cal. Pub., I: 22, et seq. 1934.

body are rich in magnetite." As a corollary to this, the bodies of titaniferous magnetite are generally associated with the darker phases, although small masses are also found to occur in pure anorthosite. It appears, from Miller's description, that the transition zone from ore to country rock is narrow, whatever the nature of the latter. The ore-bodies and other femic facies have no regular distribution with respect either to altitude or to the boundary of the intrusive. It is interesting to note that the anorthosite is notably massive, but "Magmatic flow-structure or primary foliation of the anorthosite body, particularly its femic facies, was observed in various places."

PETROGRAPHY.

The thin sections examined were taken from specimens that included examples of nearly pure anorthosite, of transitional phases, and of the rock rich in titaniferous magnetite.

The ore when examined under the microscope (Fig. 1) is seen to be composed chiefly of titaniferous magnetite, monoclinic pyroxene and apatite. A little green spinel in fractured, altered grains is present, as well as a small amount of altered mica. One or two grains of pyrite were noted.

The age relationship between the apatite and pyroxene is uncertain. Where isolated in the latter, the apatite tends to take a euhedral form, but in some cases these crystals are surrounded by radiating cracks in the pyroxene. Such a development of euhedral crystals, may not be significant. In one instance, apatite was discovered enclosing separated fragments of pyroxene that showed simultaneous extinction. As this was not duplicated anywhere else in the section, it is felt that in general the two minerals crystallized contemporaneously. As a rule, wherever the pyroxene comes in contact with anhedral apatite, the two exhibit "mutual boundaries."

Most of the magnetite is definitely later than the above minerals. The manner in which it surrounds the grains of the other minerals, with the development of a sideronitic texture, fills fractures in the apatite and pyroxene, and embraces residual inclu-

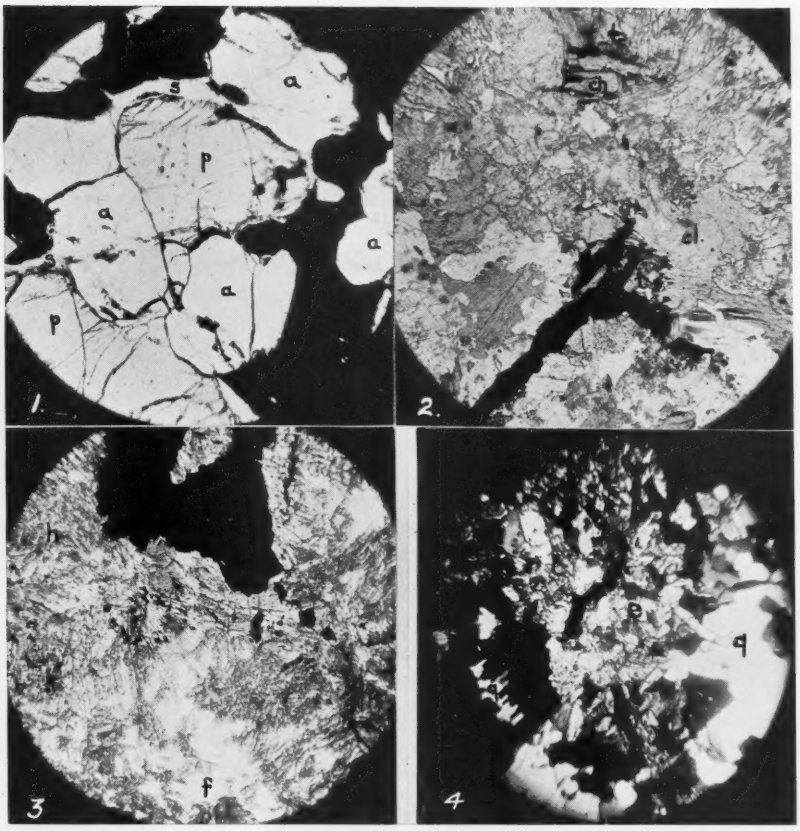


FIG. 1. Apatite (*a*) and pyroxene (*p*) with later titaniferous magnetite (black) filling fractures and growing between the grains of the older minerals, with a rim of serpentine-like mineral (*s*) separating it from the pyroxene.

FIG. 2. Magnetite (black) replacing a grain of titanite (*t*), which, with chlorite (*ch*), replaces biotite. Magnetite also later than clinozoisite (*cl*).

FIG. 3. Titaniferous magnetite (black) replacing deuteric amphibole (*h*); *f*—feldspar.

FIG. 4. Titaniferous magnetite (black), replacing epidote (*e*), and surrounded by later quartz (*q*). ×—nicols.

sions of them, leaves no possible doubt as to the relationship. It is conceivable that some magnetite, occurring as euhedral grains in a few places is early magmatic, but this criterion, by itself, is scarcely basis enough to establish two ages of magnetite.

A rather striking, although not universal, feature is the occurrence of a rim of pale green, fibrous, serpentine-like mineral, around the magnetite, wherever it is in contact with the pyroxene. The fibers are invariably perpendicular to the contact, where developed as simple rims, and definitely replace the augite, in places completely. Their relationship to the magnetite seems to be also one of replacement. Fractures in the magnetite are filled with serpentine and tongues that penetrate it exhibit strongly serrate edges. In a few instances the magnetite is smooth-bordered at its contact with the secondary minerals. However, in the latter, and paralleling the border between the two, there occurs a thin streak of magnetite grains.

The serpentine occurs as a border between apatite and magnetite in only a few cases, but in such cases the apatite does not appear to be replaced or affected. In places, a rim of magnetite separates the serpentine from the apatite.

In some cases long slender tufts and beards of tremolite extend into the pyroxene, in places completely traversing the grains in criss-cross pattern. At least a little of the magnetite is probably later than the tremolite, as evidenced by the growth of thin acicular needles of magnetite along its cleavages.

The possibility must not be overlooked that the magnetite occurring as grains and short needles in the serpentine and as slender thorns in the tremolite may differ in origin from the majority of the magnetite in the deposit. These particles may conceivably represent residuals of iron oxide released by the alteration of the pyroxene to more dominantly magnesian silicates.

A polished section of the ore when etched revealed the typical intergrowth of magnetite and ilmenite, indicating the titaniferous nature of the ores. However, the titaniferous magnetite is highly magnetic, suggesting a relatively low content of ilmenite.

Perhaps even more significant than sections of the ore are those of rather extensively modified anorthosite. These sections are composed largely of acid labradorite which is generally fairly fresh. In some sections it gives feeble, if any, evidence of twinning. It is commonly replaced by acid feldspar that forms marginal intergrowths and, more especially, incipient replacements of large areas by thin, thread-like, intricately anastomosing strands and grains. In some cases, this replacement has taken the form of thin streaks introduced parallel to the twin lamellae of the labradorite. In places the grains of feldspar show peculiar interlocking relationships.

In certain areas, the plagioclase is crushed and broken along the edges, and sprinkled with mica flakes and other products of alteration, such as epidote and clinozoisite. The mica also occurs as regularly oriented inclusions in fairly fresh labradorite.

Clinozoisite occurs in part as large grains that show good cleavage and, not uncommonly, twinning. One case was noted in which epidote made up a large area of the slide. Silicification of the feldspar also appears to have taken place in varying degree. In the much altered specimen just mentioned the quartz formed an extensive mosaic. Apatite also occurs in specimens of altered anorthosite; in general it confines itself principally to areas where hornblende or magnetite are abundant. Where it is isolated in feldspar it occupies a position on the contact between individual grains of that mineral.

The ferromagnesian minerals include green and brown biotite, and late, fine-grained acicular green hornblende that may be stained brown, a vestige possibly of an earlier mineral. The foregoing may be sprinkled with dusty magnetite. Metallic constituents include magnetite, and a few grains of pyrite altering to hematite.

With respect to the age relations of the alteration products, feldspar alters more or less extensively to epidote; mica, especially biotite, and green hornblende, appear to be later than the labradorite. The mica favors zones of granulation in the feldspars, and is apparently undeformed even where located in them. The

same is true of green hornblende, which may occur as rosettes that are obviously later. Biotite is generally replaced by chlorite, which is usually associated with epidote, enclosed in the former as spindle-shaped masses (Fig. 2). In one instance biotite is replaced by titanite and chlorite.

There is definite evidence here, too, that the magnetite was formed rather late in the history of the rock. The magnetite is confined to those parts of the thin sections that have suffered the most alteration and granulation. The magnetite rarely occurs wholly or partially in the feldspar, and where it does, is surrounded by a radiating rim of amphibole and mica. This rim is not developed where apatite and magnetite are in contact. Magnetite fills fractures in, but does not replace, the apatite.

The magnetite contains inclusions of mica and chlorite, although the latter may represent mica residuals altered by later solutions after the magnetite had been formed. The magnetite, also, is certainly later than titanite (Fig. 2) and in some cases at least is later than epidote and clinozoisite. Often, however, evidence concerning its relations with these minerals is equivocal and may suggest partial contemporaneity.

Magnetite replaces hornblende (Fig. 3) and shows, by reflected light, traces of the structure of the replaced mineral, an observation also made in the case of mica. In some sections the evidence is not clear, and one grain of magnetite was discovered in which the hornblende radiates out perpendicular to its periphery. This might argue for a prior crystallization of the magnetite but the existence of similar radiating patches of hornblende elsewhere in the slide suggests that the magnetite has simply attacked the core. However, the fine rims of amphibole that separate the magnetite from feldspar are very similar, yet apparently they are formed after the crystallization of the oxide, as a " reaction rim."

Quartz, as developed in one altered section, seems to replace epidote and is probably later than the magnetite. It was observed surrounding tongues of magnetite that were shaped by their replacement of an earlier mineral (epidote?) along its cleav-

age (Fig. 4). The place of this earlier mineral had been entirely usurped by the quartz.

In the typical anorthosite specimens, the predominant feldspar is labradorite and the ferromagnesian minerals mica and green hornblende. The last two occur chiefly at the margins of the feldspar grains and along zones of granulation, suggesting a later crystallization for them. A certain amount of alteration is indicated by the presence of carbonate and zoisite and an indeterminable fibrous material. Dr. R. E. Grim of the Illinois Geological Survey believes that this is probably a clay mineral. It is interesting to note that one of these sections is cut by several small fractures and micro-faults, which have in part been filled with feldspar, in part with an almost isotropic alteration product, the clay mineral mentioned above.

ORIGIN.

It seems apparent from the foregoing that the titaniferous magnetite is of deuteric (pneumotectic) origin, rather than pyrogenetic. In using these terms deuteric and pneumotectic, the writer employs them in accordance with the views set forth by Gillson[6] and Graton and McLaughlin.[7]

The reasons for this conclusion are: (1) Titaniferous magnetites occur in general in association with gabbroic and anorthositic rocks. It is therefore unlikely that these ores were formed by hydrothermal solutions derived from a later intrusive. (2) The appearance of the green, later hornblende, and much of the mica, indicates a deuteric origin. In this connection, Schaller[8] believes that hydrous hornblendes and biotites may be not pyrogenetic but in general the result of late reactions in the crystallized rock. (3) The occurrence of albitization rims and intergrowths, as well as true reaction rims, associated with the mag-

[6] Gillson, J. L.: Granodiorites in the Pend Oreille District of Northern Idaho. Jour. Geol., XXXV: 22, 1927.

[7] Graton, L. C., and McLaughlin, D. H.: Further remarks on the ores of Engels, California. Econ. Geol., XIII: 85, 1918.

[8] Schaller, W. T.: Genesis of lithium pegmatites. Am. Jour. Sci., X: 278–279, 1925.

netite, are evidence of such processes.[9] (4) The relationship of the magnetite to the other minerals clearly indicates that it is a late introduction. (5) Gillson[10] has shown that alteration products such as epidote, sericite, and chlorite may be deuteric, and that titanite may also be of similar origin.

There thus seems little doubt that the general association and paragenesis suggest the dominance of deuteric processes in the formation of these deposits. The ores in question are not, therefore, by any means unique. Deuteric magnetite and ilmenite are described by Gillson, Callahan and Millar[11] in Adirondack gabbros. Colony[12] considered the magnetite deposits of southeastern New York to be of "deuteric" origin, though his use of the term is broader than most will accept.

Certain considerations complicate this picture of the development of the deposit. There is a close relationship between the pyroxene and apatite and the later magnetite in the specimens rich in the latter mineral. The texture is sideronitic, and it must seem obvious that a widespread development of magnetite along the rims of the grains of pyroxene requires that the grains be markedly non-coherent along their contacts. In other words, consolidation was probably not complete, when the magnetite was crystallized. Moreover, if the pyroxene were a primary mineral, like the feldspar, it should be, like the latter, much altered. Yet in one section studied, the pyroxene was very fresh except for the reaction rim of serpentinous mineral separating it from the magnetite.

[9] Sederholm, J. J.: On Synantetic minerals and related phenomena. Bull. de la Com. Geol. de Finland, No. 48.

Colony, R. J., The final consolidation phenomena in the crystallization of igneous rock. Jour. Geol., XXXI: 170, 1923.

Gillson, J. L., Callahan, W. H., and Millar, W. B.: Adirondack Studies: The age of certain of the Adirondack gabbros, and the origin of the reaction rims and peculiar border phases found in them. Jour. Geol., XXXVI: 156, 1928.

[10] Gillson, J. L.: Granodiorites in the Pend Oreille District of Northern Idaho. Jour. Geol., XXXV: 18–19, 1927.

[11] Gillson, J. L., Callahan, W. H., and Millar, W. B.: *op. cit.*, p. 162.

[12] Colony, R. J.: The magnetite iron deposits of southeastern New York. N. Y. State Museum Bull., Nos. 249–250; 70, 1923.

Further evidence in this direction is supplied by the distribution of the magnetite-bearing segregates. As indicated earlier, they show no tendency of gravitative segregation to the borders of the anorthosite,[13] as one would expect in the case of early crystallization of these heavy minerals from a liquid magma.

The proposal is made, therefore, that these ores represent a pegmatitic development in the anorthosite magma. It is a well known fact that in the case of such rocks as diabase, the ferromagnesian minerals succeed the feldspars in crystallization. So, just as the acid extracts of a granite may concentrate to form normal pegmatites, in the case of the anorthosite there seems no reason why, with the presence of the necessary solvents, basic residues of its crystallizing magma might not accumulate to form basic phases such as the magnetite-rich rock.

Support for this theory is supplied by A. N. Zavaritsky[14] in his article on the "Classification of Magmatic Ore-Deposits." He states that "recent investigations show that the magnetite magma was apparently similar in its physical properties to pegmatitic magma, rich in mineralizing agents."

The process of accumulation of these fluid residues may be attributed to diffusion of the mobile separates during crystallization, facilitated, perhaps, by the continued movement of the crystallizing magma, movement that is demonstrated by the primary foliation of the anorthosite.

Considerable quantities of active solutions must have accompanied this pegmatitic phase, solutions that permeated the surrounding, still warm anorthosite, modifying it by the various deuteric processes that have been outlined. In this connection, it is well to remark that "deuteric" as well as hydrothermal (in the usual sense of the word) processes appear to yield a distinct paragenesis. Thus, though considerable overlap in the period of crystallization is apparent, the deuteric biotites and amphiboles were probably among the first to form. They were replaced by

[13] Miller, W. J., *op. cit.*, p. 23.

[14] Zavaritsky, A. N.: Classification of magmatic ore deposits. ECON. GEOL., XXII: 683, 1927.

chlorite, epidote and clinozoisite, and titanite, and these, in their turn, suffered some attack by magnetite and quartz.

It is apparent that an extension of this process may give rise to the various modifications that have been noted by other investigators. Intrusive features of titaniferous magnetite deposits could easily result if solidified portions of the parent magma were fractured, and continued dynamic pressure squeezed the cooling fluid segregates into the fractures as dikes. If the content of volatiles, and, therefore, the fluidity, of this differentiate were high, then this last process would provide, instead, deposits with more characteristically hydrothermal features.

In conclusion, it is clear that these titaniferous magnetite deposits are deuteric, due to hydrothermal or pneumatolytic solutions born of the crystallization of the country rock itself. These deuteric effects have not merely involved the alteration of pyrogenetic minerals and the crystallization of late-phase minerals, but have achieved also the formation of pegmatite-like, magnetite-apatite-pyroxene bodies, as residual products of crystallization. The process is similar to the formation of acid pegmatites, save that the solutions responsible have not been in sufficient quantity, nor vigorous enough, to venture beyond the boundaries of the parent rock. This is a feature generally attributed to basic igneous rocks.

ACKNOWLEDGMENTS.

The writer is indebted to Professor H. Ries for suggesting and guiding the study, and to Dr. R. E. Grim of the Illinois State Geological Survey for advice in connection with one of the sections.

CORNELL UNIVERSITY,
ITHACA, N. Y.
August 1, 1938.

SULPHATE MINERALS OF THE COMSTOCK LODE, NEVADA.[1]

CHARLES MILTON AND W. D. JOHNSTON, JR.

ABSTRACT.

Seventeen representative samples of supergene sulphates from old workings on the Comstock Lode are described. They range from simple minerals such as gypsum and epsomite to complex aggregates of four or more distinct species. All are well known species except a mineral of the copper (chalcanthite) or magnesium sulphate pentahydrate group, with about half the magnesium replaced by copper, zinc, ferrous iron, and manganese. Four new analyses of Comstock Lode mine waters are given.

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Alunogen, epsomite, gypsum, copiapite, and rhomboclase ... 767
Composition of the samples 769
Mine waters 769

INTRODUCTION.

IN THE course of a recent investigation of the accessible mine workings of the Comstock Lode, all of the members of the party were impressed by the variety of form and color of the supergene

[1] Published by permission of the Director, U. S. Geological Survey.

sulphates that formed stalactites, crusts, and efflorescences on the walls and timbers of the old workings. To determine the composition of these deposits, Dr. V. P. Gianella, of the Nevada State Bureau of Mines, and Mr. Johnston collected seventeen representative samples of the sulphates, sealed them underground in tin cans by means of friction tape and shipped them for examination to the Chemical Laboratory of the Geological Survey. At the same time four half-gallon samples of mine waters were collected and sent to the laboratory. The waters were analyzed very soon after opening. The sulphates were exposed to the air of the laboratory for variable periods of one to eight months; there appeared, however, to be only minor changes in composition, if any, resulting from the exposure.

The samples were obtained in the following workings:

1. The Central Tunnel and connected shallow workings in Consolidated Virginia, California, and Ophir ground.
2. The tunnel of the Arizona Comstock and connected shallow workings in Hale and Norcross ground.
3. The Silver Hill mine, shallow workings.
4. The Sutro Tunnel and its north and south laterals.
5. The Alta shaft; old workings approximately 50 ft. above the 1,100 or Sutro Tunnel level.

Fig. 1 is a section through the Sutro Tunnel showing the approximate position of some of the samples.

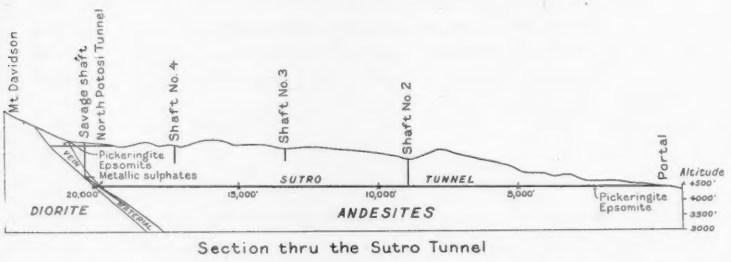


FIG. 1. A section through the Sutro Tunnel showing the approximate position of some of the samples described.

Thanks are due to Dr. Gianella who aided in collecting the specimens; to Miss Margaret Foster, of the Water Resources laboratory of the Survey, for assistance in the determination of fluorine in the waters; to Miss J. J. Glass for precise refractive index determinations; and to Dr. W. T. Schaller, of the Chemical Laboratory of the Survey, for unfailing advice whenever mineralogical difficulties appeared.

SULPHATE MINERALS.

The seventeen representative samples of the incrustations, stalactitic formations, and similar deposits in the mine are all sulphates, varying from simple minerals, such as gypsum, to complex mixtures of four or more distinct species. The individual crystals are, for the most part, of microscopic size and the specimens are not suitable for any precise goniometrical determinations. With one exception, all of the samples consist of well-known mineral species, the exception being a mineral of the copper or magnesium sulphate pentahydrate group, with about half the magnesium replaced by copper, zinc, ferrous iron, and manganese, in the order named.

The identification of the different mineral species was based on the usual petrographic and analytical procedures, supplemented by microchemical tests where indicated. The object of the investigation being the identification of the minerals present, exact and refined analytical methods were not called for. The heterogeneous and varying nature of the material available for analysis would have made precise analyses of no greater value than less exact, though sufficiently accurate, procedures. For most of the samples, therefore, the different metallic oxides and the acid (sulphuric in each case) were determined by the usual methods, and, after determination of the insoluble fraction, water was reckoned by difference. A fair degree of correspondence was obtained between the composition of the sample, as computed from the analysis, and the observed minerals, shown by the microscope.

A test for silver was made on a composite sample of the seventeen sulphate specimens with negative results.

The following species were identified: Gypsum $CaO \cdot SO_3 \cdot 2H_2O$; Epsomite $MgO \cdot SO_3 \cdot 7H_2O$; Melanterite $FeO \cdot SO_3 \cdot 7H_2O$; Goslarite $ZnO \cdot SO_3 \cdot 7H_2O$ including magnesian and cuprian varieties; Magnesium-copper-zinc sulphate pentahydrate; Pickeringite $MgO \cdot Al_2O_3 \cdot 4SO_3 \cdot 22H_2O$ including zinc, iron, and manganese varieties; Alunogen $Al_2O_3 \cdot 3SO_3 \cdot 16H_2O$; Copiapite $2Fe_2O_3 \cdot 5SO_3 \cdot 19H_2O$ (?); Coquimbite $Fe_2O_3 \cdot 3SO_3 \cdot 9H_2O$; Voltaite $3(K_2Fe)O \cdot 2(Al, Fe)_2O_3 \cdot 6SO_3 \cdot 9H_2O$ (?). Of uncertain determination were: Rhomboclase $Fe_2O_3 \cdot 4SO_3 \cdot 9H_2O$; and some poorly crystallized basic sulphates.

The seventeen samples may be grouped into three divisions as follows:

A. Simple one-mineral deposits. There are eight of these.

Gypsum (S.S. 6200) and (36J45)
Epsomite (36J17), (36J21) and (36J36)
Melanterite (36J91)
Magnesian goslarite (36J16)
Magnesian cuprian ferroan goslarite (36J15)

B. Two-mineral deposits. There are five of these.

Pickeringite-epsomite (36J11), (36J18), (36J31), and (ST. 2260)
Pickeringite—RO pentahydrate (36J12)

C. Complex deposits with ferric sulphates. Four of these.

Copiapite-pickeringite with a little epsomite and basic ferric sulphate (36J19)
Copiapite-pickeringite-epsomite-voltaite (36J20)
Copiapite-pickeringite-alunogen-coquimbite (SN. 1900)
Copiapite-alunogen-epsomite-rhomboclase (36J10)

The first group includes fairly water-soluble sulphates which, except possibly melanterite, neither hydrolyze to basic salts nor oxidize to insoluble compounds. They are thus easily carried in solution and effectively removed from the place of their origin and association of contemporaneously-formed minerals.

The second group is a mixture of pickeringite with the hepta- or penta-hydrate of magnesium sulphate; these are also quite soluble, and their solution should be fairly stable under a variety of

conditions. In general, conditions favoring precipitation of pickeringite should favor precipitation of the accompanying minerals.

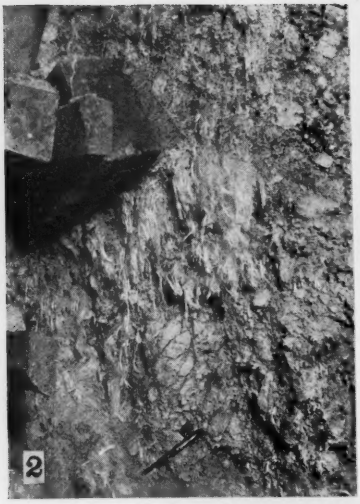
The third group is more complex, some of the constituent minerals being of low solubility. It is characterized by the presence of the ferric sulphate minerals. It is unlikely that these have traveled far from their points of origin; they indicate complex equilibria between oxidizing acid solutions and solid rock, which supplied the aluminum, potassium, magnesium, etc., present in these minerals. The oxidation of pyrite would furnish the acid ferric-iron sulphates characteristic of this group.

A. One-mineral Samples.

Gypsum.—Specimen no. S.S. 6200, from the south lateral of the Sutro Tunnel, 6,200 feet from its junction with the main tunnel and specimen no. 36J45 from a stope above the 1,100-foot level of the Alta shaft. Radiating blades, several millimeters long, and in more finely crystallized aggregates.

Epsomite.—Specimen no. 36J36, from the Arizona-Comstock 365 foot level. Abundant beard-like masses pendant from the roof of the drift. In places large masses have fallen from their support and collected on the floor or on old timbers (Figs. 2 and 3). White and finely fibrous almost like asbestos, with a little water-insoluble brownish clay. Fairly pure magnesium sulphate, with a little zinc and manganese, probably less than one per cent. Under the microscope the fibers are seen to be not homogeneous; under crossed nicols they are seen to be made up of a fine-grained mosaic of variously oriented particles. This indicates partial dehydration of the original heptahydrate to a lower hydrate.

Specimens nos. 36J17 and 36J21 from the 231 foot level of the California Mine, accessible in 1936 through the Central Tunnel. Beardlike masses pendant from the roof of the drift, and composed of a felt of delicate white fibers with the properties of epsomite. Sample no. 36J21 contained about 12 per cent of water insoluble earthy material and analysis of the water soluble portion gave



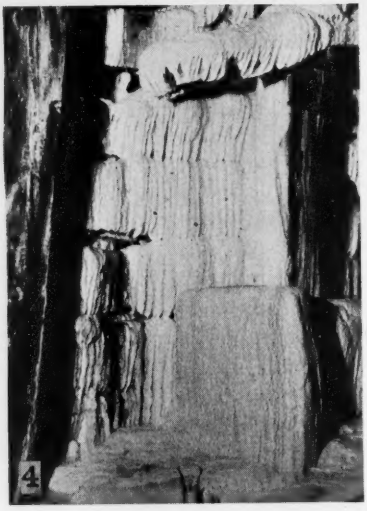
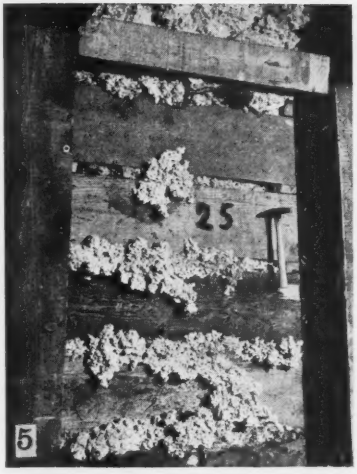


FIG. 2. "Feathers" of epsomite on quartz vein. Arizona Comstock 365 level.

FIG. 3. Epsomite growing behind and falling on lagging. Arizona Comstock 365 level.

FIG. 4. Calcite deposited on lagging and coating a barrel. Sutro Tunnel. 14,200 feet from portal. Analysis of depositing water is given on page 770.



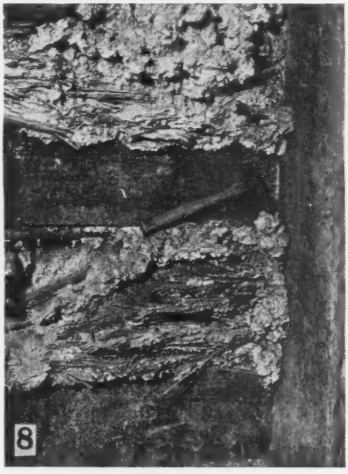


FIG. 5. Pickeringite and epsomite growing between lagging. Sutro Tunnel, north lateral.

FIG. 6. Pickeringite and epsomite aggregate breaking lagging in roof. Sutro Tunnel, north lateral.

FIG. 7. Light colored cauliflower-like masses of pickeringite and epsomite and dark stalactite of complex ferric sulphates. Sutro Tunnel, north lateral.

FIG. 8. Pickeringite and epsomite shredding lagging in zone of pyritized andesite remote from the Lode. Sutro Tunnel, 2,100 ft. from portal.

	Ratios		
Al_2O_3, Fe_2O_3, Mn_2O_3	.49		
CaO	.21		
MnO, ZnO	.30		
MgO	14.35	356	1.00
SO_3	28.77	359	1.01
H_2O (by diff.)	55.88	3104	8.72
	100.00		

The $RO : SO_3$ is almost exactly 1 : 1; the ratio of H_2O exceeds the 7 : 1 of epsomite, but this may be due to moisture of the sample, and to the water content of the insoluble portion (which was weighed after ignition).

Melanterite.—Specimen no. 36J91 from the footwall gouge of the 60 foot level of the Silver Hill mine. Leek-green or bluish-green crystals, a centimeter or so across, partly oxidized to a yellowish-brown pasty mass. The sample was moist, yielding a small excess of water. The analysis gave

	Ratios		
Insoluble	1.50		
Al_2O_3	1.09	11	
Fe_2O_3	.66	4	
FeO	23.41	326	1.00
MgO	.14	3	
SO_3	27.15	339	1.03
H_2O (by diff.)	46.05	2555	7.77
	100.00		

The analysis indicates that the sample is about 92 per cent melanterite, $FeSO_4 \cdot 7H_2O$.

Goslarite.—Two samples of goslarite were analyzed. Both samples contained several per cent of MgO and one sample contained, in addition, appreciable quantities of both CuO and FeO. In both samples, however, ZnO is the dominant base.

Specimen no. 36J16, from the 145 foot or Central tunnel level of the California mine. Vitreous and clear, very pale bluish-white crystals, in a massive crust. The exterior is altered to a

dull white powdery substance; however, optical examination shows little difference between the fresh and altered portions of the crystals, except that the dull exterior coating consists of a mass of randomly oriented brightly polarizing particles. The clear grains yield good negative interference figures of small optic angle; the refractive indices are close to $X = 1.447$, $Z = 1.470$.

Neglecting the minor constituents, the analysis indicates a composition of about 54 per cent $ZnSO_4 \cdot 7H_2O$ and 46 per cent of $MgSO_4 \cdot 7H_2O$. The calculated indices of refraction are: $\alpha = 1.446$, $\gamma = 1.473$, agreeing closely with the determined values. A very small quantity of a fibrous mineral resembling pickeringite is also present.

An analysis of the white crust gave

		Ratios		
Insoluble (mostly Fe_2O_3)	.16			
CuO	.19	2		
MnO	.20	3	349	1.00
ZnO	14.05	173		
MgO	6.90	171		
Al_2O_3, Fe_2O_3	.31		3	
SO_3	30.00		375	1.07
H_2O (by diff.)	48.19		2674	7.66
	100.00			

This analysis computes reasonably close to $(Zn, Mg)O \cdot SO_3 \cdot 7H_2O$ 98 per cent and pickeringite 2 per cent.

Although the percentage of ZnO is more than twice that of MgO, the molecular ratio of the two oxides is nearly 1 : 1, with, however, the ZnO in slight excess. Hence the material is referred to goslarite, and may be called a magnesian goslarite.

Specimen no. 36J15 from the Central tunnel level of the California mine. Pale bluish-green stalagmitic masses and incrustations, slightly coated with a dull white material. The distribution of the color is irregular, the greenish crystals grading into colorless or white.

The measured indices of refraction of the bluish-green material are $\alpha = 1.463$, $\beta = 1.475$, $\gamma = 1.480$, all $\pm .003$. Optically negative, $2V$ moderate.

An analysis of the blue-green material gave

		Ratios		
Insoluble in water (mainly Fe_2O_3)	.13			
Fe_2O_3, Al_2O_3	.30			
CuO	4.27	54		
PbO	None			
FeO	2.85	40	364	1.00
MnO	.30	4		
ZnO	11.77	145		
MgO	4.86	121		
SO_3	29.41		367	1.01
H_2O (by diff.)	46.11		2562	7.04
	100.00			

The ratios agree very closely with the general formula $RO:SO_3.7H_2O$. According to the component composition calculated from the analysis, as shown below, the calculated indices of refraction are: $\alpha = 1.454$, $\beta = 1.472$, $\gamma = 1.478$. α as determined is 1.463, the difference of .009 being greater than the error of determination, β and γ as determined are slightly higher also, but not more than the possible error of determination. The quantity of water present is almost exactly that required for the heptahydrate; it may be however that a slight degree of dehydration exists, which would tend to raise the indices; the $MgSO_4 \cdot 7H_2O$ on dehydration to $MgSO_4 \cdot 5H_2O$ changes in indices, α from 1.433 to 1.482, β from 1.455 to 1.492, γ from 1.461 to 1.493. The greatest change is in the α index.

Zinc oxide is the dominant base, both in percentage values and ratio, hence the material is goslarite, with MgO, CuO, FeO, and MnO isomorphously replacing a portion of the ZnO. The composition of the sample may be explained as an isomorphous mixture of the following components, in weight percentage, as calculated from the analysis:

$ZnO \cdot SO_3 \cdot 7H_2O$	42
$MgO \cdot SO_3 \cdot 7H_2O$	30
$CuO \cdot SO_3 \cdot 7H_2O$	16
$FeO \cdot SO_3 \cdot 7H_2O$	11
$MnO \cdot SO_3 \cdot 7H_2O$	1
	100

Of the analyses of goslarite listed by Hintze[2] several have about the same quantities of either MgO, CuO, FeO, or MnO, as the material here described; but none of the ten analyses contains such quantities of all these bases.

B. Two-mineral Samples.

Pickeringite and Epsomite.—Four of the five specimens in this group are mixtures of pickeringite and epsomite with pickeringite dominant, forming from 70 to 92 per cent of the specimen. The four analyses are grouped together in Table I in the order of increasing percentage of pickeringite.

Specimen no. 36J18 from the 231 foot level of the Central tunnel. Tough matter felt of fibers, generally white but in places pale blue, encrusting old timbers. Small irregular gray particles (up to 2 mm.) of quartz are disseminated through the crust. Some of the epsomite is in relatively large clear masses and some of it in the mosaic-like "pseudomorphous" aggregate.

Specimen no. 36J11, from the 242 foot level of the Central Tunnel. A heavy crust deposited behind the lagging, generally of a white color, but locally very pale blue. Microscopically, it is seen to consist of pickeringite and epsomite, with much of the latter apparently transformed to a mosaic of brightly polarizing particles, possibly a lower hydrate. The pickeringite gave a strong test for zinc with mercuric thiocyanate. However, only 0.99 per cent of zinc oxide was present in the composite sample analyzed, and the indications are, therefore, that the epsomite is substantially free from zinc.

Specimen no. 36J31, from the Central Tunnel level. Stalactitic, very pale blue crusts on timbers. A mass of radiating fibers, mainly pickeringite in finely twinned fasicules. A very

[2] Hintze, Carl: Handb. d. Mineralogie. 1: pt. 3, 4353, 1930.

little quartz is present. Another undetermined mineral, resembling very thin flakes of muscovite, is sparsely present. The two observed indices are close to 1.46; the mineral is optically negative with a moderate axial angle. A lower hydrate of magnesium sulphate is a possibility.

Specimen no. ST 2260 from the Sutro Tunnel is a white fibrous crust slightly coated with a yellowish or light brown film.

The analyses of these four samples are given in Table I.

TABLE I.

ANALYSES OF FOUR SAMPLES OF MIXTURES OF PICKERINGITE AND EPSOMITE.

Sample no.	36J18	36J11	36J31	ST 2260
Composition:				
Pickeringite	70	80	84	92
Epsomite	30	20	16	8
Insoluble	2.22	0.28	0.26	0.17
MgO	6.28	6.75	6.15	5.54
MnO	.72	.66	.63	.13
FeO	None	None	.34	.11
CuO	.52	.17	.87	....
ZnO	1.57	.99	.11	....
Al_2O_3	7.42	8.33	9.82	9.90
Fe_2O_3	.75	.18	None	1.11
SO_3	35.78	36.02	36.07	36.83
H_2O (by diff.)	44.74	46.62	45.75	46.21
	100.00	100.00	100.00	100.00

Pickeringite and epsomite appear to mark zones in a highly pyritized andesite. They are abundant in both north and south laterals of the Sutro Tunnel and occur in many places along the main tunnel. Approximately one-half mile from the portal of the tunnel (specimen ST 2260) and remote from the lode itself is a zone of pyritized andesite conspicuously marked by the abundant sulphates in and behind the lagging (Fig. 8). Here pyritization and subsequent oxidation are later than the precious metal mineralization, and probably later than the pyritization of the wall rocks of the Comstock Lode.

The deposition of pickeringite and epsomite causes much damage to timbers underground (Figs. 5 to 8). Lagging is dis-

placed, broken, and even shredded by the growing sulphate masses.

The fifth specimen of group *B*, specimen no 36J12, from the 242 foot level of the Central tunnel, is a massive crust, deposited on the lagging. It is composed of two distinct substances, the principal one being a light greenish-blue, massive mineral; the other, coating this, a pale brown finely fibrous and radially crystallized druse. The bluish mineral can be obtained in sufficient quantity for analysis, but the brown fibers cannot be separated from the blue sufficiently well, and themselves are not homogeneous. From optical and chemical study, however, they are essentially pickeringite mixed with a brown ferric sulphate.

The blue mineral belongs to the triclinic chalcanthite group, with the general formula $RO \cdot SO_3 \cdot 5H_2O$. The analysis shows that it is dominantly magnesium sulphate but copper, zinc, and in minor quantity, iron and manganese, are also present. Expressed as sulphate molecules with $5H_2O$, these last four components together constitute 50 per cent of the mineral.

The optical properties, determined by Miss J. J. Glass of the Geological Survey, are as follows: $\alpha = 1.495$, $\beta = 1.512$, $\gamma = 1.518$, negative with $2V = 55°$, dispersion $r < v$. Habit fine granular or slightly platy, color in transmitted light pale sky blue with no observable pleochroism.

The bluish mineral has the following composition:

	Analysis	Ratios		
Insoluble	0.20	....		
MgO	9.40	0.233		
MnO	.30	.004		
FeO	1.36	.019	.438	1.00
CuO	9.00	.113		
ZnO	5.60	.069		
Al_2O_3	Trace			
SO_3	35.07	.438		1.00
H_2O (by diff.)	39.07	2.168		4.95
	100.00			

The mineral has the following component composition, by weight percentage:

$MgO \cdot SO_3 \cdot 5H_2O$	50
$CuO \cdot SO_3 \cdot 5H_2O$	27
$ZnO \cdot SO_3 \cdot 5H_2O$	17
$FeO \cdot SO_3 \cdot 5H_2O$	5
$MnO \cdot SO_3 \cdot 5H_2O$	1
	100

Based on the component composition given above, the measured and calculated indices of refraction show good agreement.

Measured	Calculated
α 1.495	1.498
β 1.512	1.513
γ 1.518	1.517
$\gamma - \alpha$ .023	.019

The ratios obtained from the analysis are very close to 1 : 1 : 5, indicating that the mineral is a pentahydrate, with MgO the principal base. Although not recognized as an established species and hence not named, magnesium sulphate pentahydrate has been described several times in the literature. An analysis of apparently the pentahydrate of magnesium sulphate from the Cripple Creek district, Colorado, was published[3] by Hobbs in 1905. The analysis, by W. O. Hotchkiss, is given in column 1 of Table II. The material was called "epsomite." Three years later, Keller published[4] an analysis of a copper bearing magnesium sulphate pentahydrate. His material occurred as earthy, friable, bluish-white masses, associated with chalcanthite, from Copaquire, Province of Tarapaca, Chile. From his analysis (no. 2, Table II), the ratios of $RO : SO_3 : H_2O$ are calculated as 1.05 : 1.03 : 4.92, or essentially 1 : 1 : 5. Expressed in component composition the Chilean mineral consists of:

$MgO \cdot SO_3 \cdot 5H_2O$	58
$CuO \cdot SO_3 \cdot 5H_2O$	38
$FeO \cdot SO_3 \cdot 5H_2O$	3
$MnO \cdot SO_3 \cdot 5H_2O$	1
	100

[3] Hobbs, W. H.: Contributions from the mineralogical laboratory of the University of Wisconsin. Am. Geol. 36: 184, 1905.

[4] Keller, H. F.: Notes on some Chilean copper minerals. Am. Philos. Soc. Proc., 47: 81–82, 1908.

The mineral from Nevada (no. 4, Table II) is similar in composition to the Chilean mineral except that considerable zinc is present.

The cupromagnesite from Vesuvius, a sulphate of copper and magnesium, is of unknown hydration. From its water solution, crystals of the heptahydrate crystallized out.

Practically pure magnesium sulphate pentahydrate, a natural dehydration product of epsomite and showing a pseudomorphous structure microscopically, being an aggregate of minute variously oriented grains, was described[5] by Allen and Day from The Geysers, near Cloverdale, Sonoma County, California. The analysis (no. 3, Table II), shows that the material was almost of ideal purity.

The available analyses of magnesium sulphate pentahydrate from four localities are brought together in Table II.

TABLE II.

ANALYSES OF NATURAL MAGNESIUM SULPHATE PENTAHYDRATE.

	1 Colorado	2 Chile	3 California	4 Nevada	5 Calculated
MgO	19.35	11.39	17.91	9.40	19.15
CuO	....	12.43	....	9.00	....
ZnO	....	....	....	5.60	....
FeO	....	1.01	.23	1.36	....
MnO	....	.32	.14	.30	....
NiO	....	.06	.11	....	....
CaO	....	....	.13	....	....
SO_3	38.51	35.70	38.13	35.07	38.07
H_2O	42.03	38.38	42.97	39.07	42.78
Insol.	....	....	....	.20	....
	99.89	99.29	99.62	100.00	100.00

Although copper is present in two of the analyses to a considerable extent and zinc and iron in smaller but appreciable quantities, magnesium is the principal base of all. Nevertheless, the writers are hesitant about proposing a mineralogical name for the pentahydrate at present chiefly because the mineral from Nevada is only half magnesium sulphate and also because other

[5] Allen, E. T., and Day, A. L.: Steam wells and other thermal activity at "The Geysers," California. Carnegie Inst. Wash., Pub. 378: 42, 1927.

properties, such as the optical ones, are not clearly defined for the pure magnesium salt.

According to Merwin [6] there may be three modifications of $MgO \cdot SO_3 \cdot 5H_2O$. The relations of hexahydrite, described as the hexahydrate of magnesium sulphate, to the penta- and hepta-hydrates, are not yet clearly established.

C. Complex Samples with Ferric Sulphates.

All four samples of this complex group contain copiapite mixed with other ferric sulphates and other iron-free sulphates.

Pickeringite, Copiapite, and Epsomite.—Specimen no. 36J19 from the 231 foot level of the Central Tunnel. Massive crust, part of it like wet snow (pickeringite), the other part like finely divided sulphur (copiapite), with a small sprinkling of a saffron-colored material. A little epsomite was also noted.

The pickeringite is crystallized in the usual hair-like needles which gave decided microchemical tests for aluminum and magnesium, with minor reactions for zinc and manganese. The copiapite shows the usual aggregate of microscopic plates, with good crystallographic development, and refractive indices considerably above and below 1.55. The saffron mineral is indistinguishable from the yellow copiapite, except by a somewhat deeper color under the microscope, and is a somewhat more basic (?) ferric sulphate derived by a slight hydrolysis of the yellow copiapite.

Pickeringite, Copiapite, Alunogen, and Coquimbite.—Specimen no. SN 1900 from the north lateral of the Sutro Tunnel 1,900 feet from its junction with the main tunnel. Lumps of white crystalline material, heavily coated with scales of copiapite. Masses of this mineral alone are also present. Also noted were dark brown or greenish black particles, associated with fragments of quartzitic rock.

The white material consists of relatively coarsely-crystallized alunogen, fibrous crystals of pickeringite, and a finely crystallized

[6] Personal communications to W. T. Schaller, May 16, 1938, and June 6, 1938.

coquimbite, resembling wet snow in appearance. All of these are fine-grained, no crystals being larger than half a millimeter.

The alunogen consists of glistening white crystalline masses, colorless under the microscope. The mean index of refraction is close to 1.47, the birefringence around 0.01. It is readily soluble in water, gives no test for iron, and a strong test for aluminum (using cæsium chloride). The alunogen crystals resemble in outline those of the copiapite, having a similar platy habit, but are coarser and less perfectly formed.

The fibers of pickeringite are similar to those described elsewhere in this paper.

The coquimbite is colorless under the microscope, short prismatic, with positive elongation. The mean index of refraction is close to 1.55, the birefringence low, the interference color an abnormal blue. It is not readily soluble in cold water; the acid solution gives good tests for ferric iron and sulphate, a slight test for magnesium, and none for ferrous iron.

Larsen and Berman [7] list coquimbite as having a composition $Fe_2O_3 \cdot 3SO_3 \cdot 9H_2O$, uniaxial positive, with indices 1.550 and 1.556, and being soluble in water. Another listing (page 69) of a questionable coquimbite has a slightly different composition, and the mineral is described as soluble in boiling water, and has much greater birefringence. Dana [8] says coquimbite is wholly soluble in cold water, and is decomposed on boiling.

The copiapite is well crystallized, showing under the microscope a general tabular habit, with excellent development of the faces m, o, s, and b as figures in Dana's System.[9] No interference figures were obtained on the plates. Pleochroism is distinct from practically colorless to yellow. The two measured refractive indices on the plates were 1.535 and 1.59.

Larsen and Berman [10] give $\alpha = 1.530$, $\beta = 1.550$, $\gamma = 1.592$.

[7] Larsen, E. S., and Berman, Harry: The microscopic determination of the non opaque minerals. U. S. Geol. Surv., Bull. 848: 69–70, 1934.

[8] Dana, J. D., System of mineralogy, 1915, p. 956.

[9] *Op. cit.*, p. 965.

[10] *Op. cit.*, p. 104.

The very small deep green or brown or black particles and patches seem to be opaque under the microscope. It is impossible to separate them from the other constituents clearly enough for chemical determination. They may be altered voltaite.

Pickeringite, Epsomite, Copiapite, and Voltaite.—Specimen no. 36J20 from the Central Tunnel, 231 foot level. Crust on drift wall, composed of variously colored minerals, all sulphates, except for some fragments of quartz. Hydrolysis has occurred, resulting in the formation of free sulphuric acid, which has attacked the paper bag in which the samples were wrapped.

The minerals recognized are white pickeringite and epsomite, yellow copiapite, and greenish-black voltaite; in fairly equal proportions, with perhaps least of the epsomite.

The pickeringite and epsomite probably deviate in composition from the simple formulas $MgO \cdot Al_2O_3 \cdot 4SO_3 \cdot 22\ H_2O$ and $MgSO_4 \cdot 7H_2O$, respectively, for tests on the bulk sample showed both zinc and manganese to be present in minor quantity. The copiapite occurs in the usual excellent microscopic platy crystals. In part, it seems to have been altered to a darker reddish-brown substance, of variable but higher indices of refraction, suggesting a mixture of poorly defined substances.

The most interesting mineral in this aggregate is the voltaite. It forms rather conspicuous dark green masses, without any definite boundaries, intimately mixed with the other minerals. It is practically impossible to isolate it pure enough in quantities sufficient for accurate analysis, but by washing with cold water most of the other minerals may be removed. An excellent test for potassium was obtained from the material thus cleaned, also tests for ferrous and ferric iron. The larger masses do not show clearly-defined optical characters, some parts being apparently isotropic. Other parts have a vague radial crystallization. Good crystals, however, of microscopic size, can be found enmeshed in the pickeringite and especially the copiapite aggregates. These are dark-green (lighter-green by transmitted light), of high index, near 1.59, and low birefringence. Under crossed nicols some appear to be isotropic; the variously-birefringent segments of

others suggest fourlings or fivelings, as have been previously described for voltaite.

In view of the complex and uncertain formula for voltaite, and the heterogeneity of the sample, an analysis was not undertaken, as its interpretation would rest on too many variable assumptions.

Alunogen, Epsomite, Gypsum, Copiapite, and Rhomboclase.—Specimen no. 36J10 from the Central Tunnel level. Stalactitic crusts, the individual stalactites averaging 1 to 2 centimeters in length and about a centimeter thick, showing concentric banding on a very fine scale, with the interior portion pale-yellow, the outer brick-red. With a hand lens the pale-yellow interior is seen to consist of two materials, one granular like tiny grains of sulphur, and the other glistening colorless micaceous appearing scales.

Optical examination, supplemented by qualitative tests, showed the outer brick-red zones to be of rather variable nature, both in the indices of refraction, ranging below and above 1.57, and in intensity of color. Some of it appears uncrystallized and some an exceedingly fine-grained aggregate of brightly polarized particles. From the bulk analysis given below it is inferred that the material is a basic ferric sulphate, related to rhomboclase, $Fe_2O_3 \cdot 4SO_3 \cdot 9H_2O$. Its precise nature cannot be determined, owing to its complexity. Scattered about the outermost brown shell are numerous bright red or scarlet masses of microscopic size. They have rounded contours, rather than angular, and appear to be hygroscopic, to some degree liquid. They may be a saturated solution of ferric sulphate in equilibrium with a crystalline phase of some basic ferric sulphate.[11]

The sulphur-yellow particles are too fine-grained for any definite microscopic study. They appear to have rather high indices and birefringence, and may be copiapite.

[11] Concerning this, Hintze, (*op. cit.*, p. 4394) states that all the mineral ferric sulphates, including both the truly basic and the so-called "normal" sals, are ferric hydroxy-compounds. Even the "acid ferric sulphate" is considered to be a hydroxy-compound, derived from complex ferrisulphuric acids, of which botryogen and roemerite are salts. Hintze further classes the basic ferric sulphates according to the $SO_3:Fe_2O_3$ ratio, varying from 3:1 in coquimbite to less than 1:1 in amorphous gels such as glockerite and pissophane.

The colorless micaceous-appearing material resolves itself under the microscope into two distinct minerals, one having the characters of epsomite, the other, present in about equal quantity, consisting of minute flakes of very low birefringence, with the lowest observed index near 1.46, and the highest near 1.465. From the mixture of the two minerals (it being impossible to separate them) a fair test for ferric iron and a strong test for aluminum were obtained; it is therefore inferred that the weakly-polarizing flakes are a basic aluminum sulphate, with some ferric iron isomorphously present. Much difficulty was found in determining the optical character; the plates were very small, and gave a vague figure of possibly negative character. These characters accord with those of alunogen, which has a platy development parallel to (010), to which the obtuse bisectrix is normal. The small optic angle can only be observed on the acute bisectrix, which is nearly parallel to the plates.

Besides the epsomite and alunogen, minute quantities of sharp prisms, extinguishing around 45°, and showing "swallow-tail" cleavage and terminal re-entrant angles, were seen; they have indices near 1.52, and are probably gypsum. It is also possible that a little pickeringite is also present. It thus appears that in addition to the identified epsomite and alunogen, there are less certainly determined basic ferric sulphates, as rhomboclase and copiapite, and, in very minor quantity, gypsum and pickeringite.

An analysis of one of the stalactites gave:

		Ratios
Insoluble	.13	
CuO	.19	2
FeO	.83	11
MgO	4.31	107
CaO	Trace	
MnO	.65	9
ZnO	Trace	
Al_2O_3	6.74	66
Fe_2O_3	8.49	54
SO_3	35.63	445
H_2O (by diff.)	43.03	2388
	100.00	

This analysis may be computed into 42 per cent alunogen, 30 per cent epsomite, and the remainder basic ferric sulphates such as rhomboclase and copiapite. The computation, however, is

merely an approximation to the actual composition of the complex stalactites.

Composition of the Samples.

Table III recapitulates the mineralogical composition of the seventeen samples. The figures represent approximate percentage of the entire sample. *X* indicates the mineral is abundant in the sample and *x* that it is present in small quantities.

TABLE III.

Mineral	Sample number																	
	36J91	36J16	36J21	36J17	36J36	36J15	36J12	36J11	36J18	36J31	ST 2260	36J19	SN 1900	36J20	36J10	SS 6200	36J45
Gypsum															*x*	100	100
Epsomite			88	88	99			20	30	16	8	*x*		*X*	*X*		
Goslarite		98				99											
Melanterite	92																
Magnesium sulphate pentahydrate							*X*										
Pickeringite		2					*x*	80	68	84	92	*X*	*X*	*X*	?		
Coquimbite													*X*				
Alunogen													*X*		*X*		
Copiapite												*X*	*X*	*X*	?		
Voltaite													?	*X*			
Rhomboclase															?		
Basic ferric sulphates							*x*					*x*					
Clay, etc.	8		12	12	1	1			2								

MINE WATERS.

Analyses of eight samples of mine waters from the Comstock Lode are given in Table IV. Of these, nos. 1 to 4 are new and nos. 5 to 8 have been taken from published reports. With the exception of no. 8, the waters are all of the same general type being essentially solutions of calcium (magnesium, sodium, potassium) sulphate and bicarbonate or carbonate. Nos, 2, 3, 4, and 5 are cold water of undoubted meteoric origin that have descended these fissures and old mine workings and have dissolved mineral matter en route. They differ very little from the hot waters represented by analyses 1, 6, and 7 except that the two

samples from deep workings (nos. 6 and 7) contain less carbonate in solution.

TABLE IV.

MINE WATERS OF THE COMSTOCK LODE, NEVADA.
(Parts per million.)

	1	2	3	4	5	6	7	8
	Yellow Jacket Sutro Tunnel level	Central Tunnel	Sutro Tunnel	Hale and Norcross Sutro Tunnel level	Savage 600′ level	C. & C. Shaft 2250′ level	Union Consol. 2650′ level	Central Tunnel
Temperature	130° F.	Cold	80° F.	Cold	...	Hot	130° F.	Cold
CO_3	None	None	None	None	....	....	9.3	....
HCO_3	387	184	301	307	236	41.7	None	....
SO_4	972	725	320	1,302	380.7	474.8	752	193,450
Cl	8	34	10	14	1.3	19.0	12.0	128
HS′	0.3	None	None	0.8	....	....	....	....
F	0.8	0.4	None	0.8	....	....	....	....
Ca	334	217	141	218	148.3	100.4	204.0	1,244
Mg	82	86	31	113	20.9	5.8	4.0	6,519
Na	55	32	54	45	57.1	130.6	145.0	535
K	10	15	9	9	8.4	53.4	8.4	....
Al‴	....	....	....	....	....	....	....	9,638
Fe‴	....	....	....	....	....	....	....	5,025
Mn	....	....	....	....	....	....	None	900
Cu	....	....	....	....	....	....	....	148
SiO_2	49	13	34	24	30.5	133.4	61.0	616
Al_2O_3	1.9	3.2	0.8	1.9	....	2.5	....	....
Fe_2O_3	0.7	0.6	0.4	0.6	....	9.1	None	....
OH	....	....	....	....	....	....	7.5	....
H	....	....	....	....	....	....	....	2,822
Total	1,900.7	1,310.2	901.2	2,041.6	883.2	970.7	1,203.2	221,025

1. Water flowing from cross-cut to Yellow Jacket mine on the Sutro Tunnel level. Rate of flow, 100± gal. per minute. Temperature, 130° F. (U. S. G. S. 8377). Charles Milton, analyst.

2. Central Tunnel. Descending mine water flowing one-half gal. per minute from chute on 231 ft. level (U. S. G. S. 8826). Charles Milton, analyst.

3. Drip in Sutro Tunnel about 14,200 feet from portal. Drip approximately 29 gals. per minute, 80° F. (U. S. G. S. 8829). Charles Milton, analyst.

4. Water flowing from cross-cut to the Hale and Norcross mine, Sutro Tunnel level. Rate of flow approximately 25 gal. per minute (U. S. G. S. 8876). Charles Milton, analyst.

5. Savage mine, 600 ft. level. S. W. Johnson, analyst. Ex-

plorations of the Fortieth Parallel, vol. III, p. 87. (Analysis recalculated.)

6. C. & C. Shaft, 2250 ft. level. N. E. Wilson, analyst. John A. Reid, Bull. California Univ. Dept. of Geol., vol. 4, pp. 177–199, 1905. (Analysis recalculated.)

7. Hot water (130° F.) from Union Consolidated mine, 2650 ft. level. Chase Palmer, analyst. Edson S. Bastin, Bull. U. S. G. S. 735–C, pp. 41–63.

8. Vadose water, Central Tunnel. N. E. Wilson, analyst. See paper by J. F. Reid above cited, p. 192 (analysis recalculated and adjusted). However, Wilson,[12] who analyzed no. 6, notes that his CO_2 determination is low because the sample was exposed to air for some days before analysis. Wilson also evaporated 10 liters of this water and by microscopic measurement of the assay button determined the precious metal content to be 0.298 milligrams of gold and 2.92 milligrams of silver per ton of water. This silver content—about 3 parts in a thousand million—lies very near the limit of analytical skill. Even though the results are accurate, it should be noted that sea water, from the Kristiana Fjord, Norway, was found to contain 5 to 6 milligrams of gold and 19 to 20 milligrams of silver per ton.[13]

In the analyses of Comstock waters listed, the writers see no internal evidence to support a magmatic origin for them.

Analyses 1 to 7 represent waters too dilute to deposit sulphates although some of them are depositing carbonates. Fig. 4 shows a deposit of calcium carbonate from water no. 3 that coats lagging on the wall of the tunnel and a barrel resting on the tunnel floor.

The only analysis of a highly concentrated sulphate water of the type from which the salts herein described might be deposited is no. 8. In addition to the metallic constituents determined it is probable that several hundred parts per million of zinc are also present.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Aug. 9, 1938.

[12] Reid, J. A.: The structure and genesis of the Comstock Lode, Univ. of Calif. Pub., Bull. of the Dept. of Geology, 4: 190, 1905.

[13] Clarke, F. W.: Data of geochemistry. U. S. Geol. Surv. Bull. 770: 124, 1924.

DISCUSSION AND COMMUNICATIONS

LATE GOLD AND SOME OF ITS IMPLICATIONS.

Sir:—In the March-April 1938 issue of this JOURNAL J. B. Mawdsley discusses the appearance of late gold in some Canadian gold-quartz deposits and draws the conclusion that the gold in some of them was brought in by separate solutions a considerable time after the formation of the quartz veins and their accompanying ore and gangue minerals. In some deposits, he says, part of the gold accompanied directly the vein-forming solutions, the rest of the gold content being brought in at a later stage.

As an explanation of the occurrence of late gold he assumes a separation, at a greater depth, of the emanations from the magma into two fractions, one forming the quartz veins with their various minerals, and the other depositing gold and practically nothing else. The introduction of this later, gold-bearing solution was rendered possible by fracturing of the veins, forming suitable channelways.

His conclusions are at a variance with the general opinion, held by other students regarding the deposition of gold quartz ores, and seem to be repugnant to the results obtained by detailed studies of such ores, not only from Canada but from other parts of the world as well.

Although the writer's experience of Canadian gold deposits is very incomplete, it may be of some interest to discuss the above matter, and its bearing on similar problems, from some Swedish gold deposits.

Mawdsley discusses the Red Lake Gold Shore deposit at Red Lake, Ontario, and arrives at the conclusion, "that gold has no close connection with the bulk of the vein forming material" (p. 203). This deposit is situated only about one mile N.W. of the Howey Mine; the latter was described in detail by W. B.

Mather in the March-April 1937 issue of ECONOMIC GEOLOGY. The evidence in this paper clearly brings out that gold crystallized with various ore and gangue minerals during the second stage of mineralization (p. 153). This is further emphasized by a number of excellent photomicrographs. Mather further states that "the solutions of the second stage contained Pb, Au, Cu, Bi, Te, Ag, Fe, Zn, Ca, Mg, SiO_2, H_2O, H_2S, As, Sb and CO_2" (p. 151). As regards the crystallization of quartz, Mather makes the following interesting statement (p. 146):

> Quartz contains large areas of metallic minerals joined by small sulphide stringers, which are believed to have formed by their expulsion from the former as it crystallized, and therefore the sulphides were contained in the residual solutions and their crystallization was controlled by the crystal boundaries of quartz.

Not being familiar with these particular deposits the writer does not want to make a too hasty inference, but it seems indeed unusual, that there should be such a wide difference in the occurrence of the gold, and in origin of these two closely adjoining deposits, which as to some aspects of general geology and as regards type of deposit, present some close relationships.

As Mawdsley in his paper gives the hypothesis of late gold a wide and regional significance and assumes that "much vein quartz and associated metallic minerals and many sulphide deposits have an immediate origin separate from that of gold, especially when the latter occurs in profitable concentrations" (p. 207), the writer will give some facts about the occurrence of gold in its relation to other minerals in the gold-copper-arsenic ore at Boliden [1] and in the sulphide ore at Falun.

The fine-grained, massive arsenopyrite ore at Boliden is commonly brecciated by a number of ore and gangue minerals as chalcopyrite, pyrrhotite, Pb-Sb-minerals, quartz, calcite and many others. Gold is often found associated with these and the microscopic evidence shows gold intimately intergrown with them in a manner that excludes its later introduction in a separate solution. Where quartz makes up the cement in the arsenic breccia, gold is often found in the quartz in a manner that indeed reminds

[1] Ödman, O. H.: On the mineral associations of the Boliden Ore. Geol. Fören. i Stockholm, Förhandlingar, Vol. 60, pp. 121–146, 1938.

of the appearance of gold in some of the deposits mentioned by Mawdsley. Also here the microscopic study manifests the close relationship between gold and the other ore minerals. The crystallization of the cement of the breccia was evidently one continuous process, and it seems to the writer that the explanation given by Mather (p. 146) and cited above will give the most logical interpretation also in this case.

Of immediate interest in connection with the Canadian deposits is the occurrence at Boliden of gold-bearing quartz-tourmaline veins and lenses. In these ores, native gold is of common occurrence and it is particularly enriched at such places where also the other ore minerals (as pyrrhotite, chalcopyrite, bismuth, complex sulphosalts etc.) are present in large amounts. The evidence of the contemporaneous introduction of the vein matter and its crystallization from one solution is overwhelming. The gold has evidently been in a highly mobile state because thin sheets of the metal have been deposited on the cleavage planes of the sericite-schist next to the veins.

Gold is also found in the pyrite ore in positions that indicate it to be a product of the main pyrite mineralization. In one case a wedge of pyrite ore penetrated the schist a short distance and ended with a narrow quartz vein which petered out in a fissure. The quartz vein contained chalcopyrite and visible gold.

Many other examples from Boliden could be mentioned, all indicating that the gold of each stage of ore deposition crystallized with the other ore and gangue minerals from a single, complex solution.

At the famous old Falu mine in Central Sweden, quartzose gold ore has a limited distribution. The ore occurs as veins and silicified portions of the wall rocks and is composed of gold, weibullite ($PbBi_2/S$, $Se/_4$), bismuth, galena, chalcopyrite, pyrite and others in a base of chiefly quartz. The investigations by Törnebohm [2] and Geijer [3] show that gold is intimately associated with the

[2] Törnebohm, A. E.: Om Falu gruvas geologi. Geol. Fören. i Stockholm, Förhandl., Vol. 15, pp. 609–690, 1893.

[3] Geijer, P. A.: Falutraktens berggrund och malmfyndigheter. Geol. Surv. of Sweden, Ser. C, No. 275, 1917. (With German summary.)

metallic minerals. In the only polished section of the ore available to the writer "large areas of metallic minerals joined by small sulphide stringers" (Mather, p. 146) were seen in the quartz. Gold was intergrown with many of the ore minerals and was distinctly replaced by some of them, *e.g.* weibullite and an unknown mineral. Geijer states (p. 286) that "the gold ores, which partly have the character of veins, probably represent the last portion of the solutions which formed the 'hard ores'" (transl. by O.H.Ö.), and it is here inferred that also gold crystallized from those solutions.

It is difficult to accept the generalization of the occurrence of late gold, or even its widespread distribution. Not only in the examples cited above, but in the majority of gold-quartz veins and gold-bearing sulphide ores most of the gold seems to follow the general mineralization, although, because of a comparatively late deposition, it often gives the impression of having been introduced later. Certain difficulties also arise in explaining the separation of gold from the other magmatic emanations. It suffices to point out that, although the metal as such has a low volatility and shows an inconsiderable chemical activity, it does form soluble compounds, or colloids as emphasized lately especially by Lindgren, and does show strong affinity to certain elements, *e.g.* tellurium, or copper. Consequently, it is more likely, that it will be adsorbed by the ascending solutions and deposited along with the other minerals of the paragenesis.

OLOF H. ÖDMAN.

BOLIDEN, SWEDEN,
June 3, 1938.

THERMODYNAMICAL CALCULATION OF THE SOLUBILITY OF SOME IMPORTANT SULPHIDES, UP TO 400° C.

Sir: Shortly after a paper on this subject had been accepted for publication in this Journal,[1] a publication of the U. S. Bureau of

[1] ECON. GEOL., 33: 34–51, 1938.

Mines by K. K. Kelley [2] brought to light much new information concerning the free energy-temperature relations for many sulphides. The values of the free energy at 25° C. adopted by Kelley in this paper are occasionally found to be in poor agreement with those given by other authors and used by the present writer in his calculations. Kelley believes, however, that the results given by his equations are the most reliable values available at present. It was thus deemed advisable to recalculate the solubility of sulphides at high temperature on the basis of these new equations, as discrepancies between the new results and those previously given (op. cit. p. 48) might indicate the approximation on these calculations. These new values are given in Table I,

TABLE I.

SOLUBILITY OF SULPHIDES, UP TO 400° C. (GMS. PER LITER).[3]

	25° C.	100° C.	200° C.	300° C	400° C.
MnS	0.2	1.5	6.10^{2}	6.10^{3}	5.10^{4}
ZnS	3.10^{-5}	2.10^{-3}	0.1	1.2	7.0
FeS_{α}	1.10^{-4}	—	—	—	—
FeS_{β}	—	—	1.10^{-2}	2.10^{-2}	4.10^{-2}
CoS	2.10^{-6}	1.10^{-5}	5.10^{-5}	1.10^{-4}	4.10^{-4}
FeS_2	2.10^{-8}	2.10^{-7}	2.10^{-6}	8.10^{-6}	2.10^{-5}
PbS	3.10^{-9}	5.10^{-8}	6.10^{-7}	3.10^{-6}	8.10^{-6}
Ag_2S	1.10^{-12}	5.10^{-12}	2.10^{-11}	3.10^{-11}	5.10^{-11}
Cu_2S_{α}	1.10^{-12}	5.10^{-11}	—	—	—
CuS	2.10^{-13}	7.10^{-13}	3.10^{-12}	8.10^{-12}	1.10^{-11}
HgS	1.10^{-17}	7.10^{-17}	4.10^{-16}	1.10^{-15}	3.10^{-15}

[3] Calculated for a solution of pH = 7.

together with values of the solubility of sulphides which had not been considered in the first place, mainly for lack of data on specific heats at high temperature.

In the case of FeS_2 (pyrite), the iron has been assumed to be in the ferrous state. For this sulphide, furthermore, it has been necessary to develop a new relation between the solubility and the solubility product, this relation being that

$$c = \sqrt[3]{4PX},$$

[2] Kelley, K. K.: Contribution to the data on theoretical metallurgy. VII. The thermodynamic properties of sulphur and its inorganic compounds. U. S. Bur. Mines, Bull. 406, 1937.

where c is the solubility in moles per liter, P is the solubility product, and X has the same significance as before (p. 37).

The value of the solubility of CU_2S_α at 25° C. given in the previous paper was miscalculated. The solubility of this sulphide does not decrease with increasing temperature, as it appears to do on the diagram p. 49.

It should be kept in mind that for many sulphides the free energy of formation at 25° C. is not accurately known. Furthermore, $\frac{dE}{dT}$, for the metals concerned, has been assumed to remain constant throughout the temperature interval 25°–400° C. Errors of several thousand calories on the free energy of solution at high temperature are thus quite possible, and results should not be expected to give more than, roughly, the order of magnitude of the solubility at high temperature. These results, however, may perhaps represent the best approximation available at the present time.

JEAN VERHOOGEN.

VOLCANO NYAMLAGIRA,
BELGIAN CONGO,
July 6, 1938.

REVIEWS

Introductory Economic Geology. By W. A. TARR. 2nd Edit., pp. 645; figs. 257. McGraw Hill Book Co., New York, 1938. Price $5.00.

This textbook is designed for use by students who possess a rudimentary knowledge of geology. The general plan and arrangement of subject matter are excellent. The attention given to the practical uses of minerals and earth materials is particularly attractive and should stimulate the interest of beginning students. In parts of the book, however, the geology is greatly subordinated to the metallurgy and uses. Under the heading of magnesium, pp. 326–327, no mention of geology is made.

The style is inclined to be verbose and, with careful checking, numerous repetitions and excess words could be eliminated. In many places the meaning is obscure. On p. 27 (for example) "This means seems to possess considerable possibilities for the formation of ore deposits, for the ejected liquid may, by concentration, have become rich in several metals, which, under the new conditions in the surrounding rocks, would be deposited"; on p. 401, "Thus although the pressure due to capillarity was small, it resulted in moving the oil out of the capillary openings into the supercapillary spaces where the more active circulation due to compaction could act in furthering its expulsion." Many similar examples could be given.

The discussion of ground water is superficial and seems surprisingly inadequate in view of the objective of the book "to present . . . a general picture of the earth materials used by man." In large parts of our country, ground water is of vital importance to human existence and any comprehensive text on Economic Geology should include a discussion of the subject.

The contrast between the section discussing oil and that discussing metal deposits is noticeable. Under oil, much space is devoted to structure and structural control of deposition, but under ore deposits no attention is given to structure or structural control, although transportation of metals in solutions is commonly mentioned. One could infer that the author regards ore deposition as entirely a function of temperature and pressure.

Numerous statements suggest a lack of knowledge of recent literature and developments in geology; for example, on p. 276, "There is little doubt that the ores of the San Juan region were deposited by magmatic

solutions, as they are all related to the dioritic and monzonitic intrusives." Apparently the writer is not aware of Burbank's recent and excellent work. Under pegmatites, p. 48, intergrowths are described as resulting from crystallization at the eutectic point. "There is some doubt, however, that the intergrowths of quartz and feldspar are really eutectics, because eutectics represent the final crystallization of two mineral constituents of a solution, whereas the intergrowths of many pegmatites are the result of an initial crystallization, after which the quartz and feldspar have crystallized independently of each other." No mention is made of replacement in igneous rocks, either pegmatites or other types.

Other statements are vague. On p. 247, "There are two gold tellurides, but calaverite is the more important as a source of gold, and it is restricted to a few districts." Search fails to reveal which of the several gold-bearing tellurides is the second mineral referred to.

Although the plan of the book, on the whole, is good, and the objectives are commendable, the numerous misstatements and errors detract from its effectiveness and value as a text.

CHAS. F. PARK, JR.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Aug. 8, 1938.

Studies on the Periodicity of Earthquakes. By CHAS. DAVISON. Pp. ix + 107; figs. 14. Thos. Murby & Co., London. 1938. Price, 13s 6d.

This little book gives in condensed form the results of its author's long study of the periodicity of Earthquakes, which is believed by him to throw considerable light on sudden movements of the Earth's crust. His general thesis is that if the magnitude of the force that may produce earthquakes is subject to a periodic variation, as in annual or diurnal changes of barometric pressure, the same or a contrary periodic variation may be inpressed on the frequency of earthquakes in any district, and that the study of this periodicity may, therefore, throw light on the movements of the Earth's crust.

By listing the data on 6220 earthquakes recorded in earthquake catalogs, and discussing them mathematically he reaches certain conclusions as to the origin of their annual, diurnal and lunar periodicities and as to the significance of their eleven year, nineteen year and forty-two minute periods. After his discussion he summarizes his interpretation of the results and concludes that inferences may be fairly reached as to whether the movements of the crust producing earthquakes of different classes are upheavals or depressions.

W. S. BAYLEY.

The Municipal Ground Water Supplies of North Dakota. By G. A. ABBOTT AND F. W. VOEDISCH. Pp. 99; figs. 19; tables 9; pl. 2; N. Dakota Geol. Surv., Bull. 11, Fargo, 1938.

Because of inadequate surface supply, much of the water supply of North Dakota must be drawn from underground sources. A large portion of the ground water used in the state is of such poor quality as to be unfit for human consumption and this condition has been aggravated in recent years by the droughts that have reduced the volume of shallow sources and forced the increased use of deeper, more highly mineralized waters. As a preliminary to the development of better supplies, the surveys reported in this bulletin were undertaken with the aid of Federal relief agencies. The data in the report include chemical analyses of water from 509 sources of underground supply in 295 communities. Of general interest to students of water supply in the region are the correlations between quality of water and the formation from which it is drawn. Sources include alluvium, glacial lake deposits, outwash, and drift, and bed-rock formations from the Fort Union through the Dakota. Fluoride exceeds permissible limits in some of the waters, particularly those from deeper formations.

EDWARD L. TULLIS.

SOUTH DAKOTA STATE SCHOOL OF MINES,
RAPID CITY, SOUTH DAKOTA.

Mineralogie von Bolivien. By FR. AHLFELD UND J. MUÑOZ REYES. Pp. vii + 89. Figs. 30. Gebrüder Borntraeger, Berlin. 1938. Price, 10.50 RM.

In order to provide for a more general distribution of knowledge of Bolivia's mineral resources the authors have furnished in a condensed form, in German, their larger treatise, "Mineralogia Boliviana," which was written in Spanish. The book contains descriptions of 171 minerals of which 9 are metals, 32 sulphides and sulpho salts, 19 oxides and hydroxides, 5 haloids, 1 a borate, 10 carbonates, 22 sulphates, molybdates or tungstates, 23 phosphates, arsenates, vanadates or niobates, 21 silicates of economic importance and 2 organic compounds. The descriptions are brief, but satisfactory, and there is provided a 7 page index of localities.

W. S. BAYLEY.

Les minerais de cuivre du Sud-Katanga. By MARCEL GYSIN. Pp. 139; figs. 12; pl. 5. Com. Spéc. du Katanga, Ann. du Serv. des Mines, vol. 7, 1936. Brussels, 1937.

This is a good report on the geology and copper minerals south of Katanga. First is given an 8-page résumé of the rock formations and structure; then follow two short chapters on the deposits and minerals of

Musoshi, Kinsenda, and Lubembe. These recently discovered deposits lie just north and east of the Rhodesian Copper Belt and southeast of the better known carbonate deposits of Katanga. A comparative study follows between these deposits and the Rhodesian deposits with respect to the intrusives, hypogene and supergene sulphides, and oxidation. Hypogene and supergene chalcocite, covellite, bornite, chalcopyrite, and linnaeite are described. The literature has been carefully reviewed.

An Orientation in Science. By C. W. WATKEYS, chief editor. Pp. 560; figs. 280. McGraw-Hill Book Co., New York, 1938. Price, $3.50.

This survey of science by ten members of the University of Rochester faculty is offered as a first year college text to introduce the student to the broad field of science. It emphasizes the scientific method of thought and procedure, the basic principles and problems of science and the interrelationships of the various sciences. A few principles, rather than a mass of facts, are used to convey the conception of science to the student. There are chapters on astronomy, geology, chemistry, physics, biology, paleontology, physiology, bacteriology, psychology, mathematics and the scientific method. The essentials of each field are covered. It is written clearly for student or lay reader, and for those who desire such orientation courses it should prove useful.

BOOKS RECEIVED.

J. D. BATEMAN.

Lower Pliocene Mollusks and Echinoids from the Los Angeles Basin California. W. P. WOODRING. Pp. 67; pl. 9; figs. 2. U. S. Geol. Surv. Prof. Paper 190. Washington, 1938. Price, 30 cts. *Paleontology of oil-bearing strata.*

Pliocene Diatoms from the Kettleman Hills, California. K. E. LOHMAN. Pp. 22; pl. 4. U. S. Geol. Surv. Prof. Paper 189–C. Washington, 1938. Price, 15 cts.

Drought of 1936 with Discussion of the Significance of Drought in Relation to Climate. JOHN C. HOYT. Pp. 62; pl. 2; figs. 18. U. S. Geol. Surv. W. S. P. 820. Washington, 1938. Price, 15 cts.

Comparative Pulverized Fuel Boiler Tests on British Columbia and Alberta Coals and on Ontario Lignite. C. E. BATTZER AND E. S. MALLOCH. Pp. 54; pl. 1; figs. 2. Canada Bur. Mines. Pub. No. 790. Ottawa, 1938. Price, 25 cts.

Preliminary Statement on the Mineral Production of the Province of Quebec, 1937. Quebec Bureau of Mines. Pp. 11. Quebec, 1938. *Statistical.*

Chromite Deposits in Oregon. JOHN E. ALLEN AND OTHERS. Pp. 73; pl. 2; figs. 11. Oregon Dept. Geol. and Min. Indus. Bull. 9. Portland, 1938. Price, 50 cts. *Regional review; good bibliography.*

Geology and Mineral Resources of the Gold Coast. N. R. JUNNER. Pp. 11, map 1. G. C. Geol. Surv. Accra, Gold Coast, 1938. *Brief resumé.*

Mining in the Gold Coast. H. G. MOUNTAIN. Pp. 8; figs. 3. G. C. Dept. Mines. Tarka, Gold Coast, 1938. *Statistical.*

Work of the New Jersey Geodetic Control Survey. ARTHUR NOACK. Pp. 14; maps 68. N. J. Dept. Conservation. Bull. 46. Trenton, 1938. *Report of W. P. A. local mapping project; principally maps.*

Publications on the Geology, Mineral Resources, and Mineral Industries of Illinois. M. M. LEIGHTON. Pp. 112; Ill. Geol. Surv. Urbana, 1938. *Abstracts of all publications and complete index.*

Minerals Yearbook, 1938. H. H. HUGHES. Pp. 1339. U. S. Bur. of Mines. Washington, 1938. Price $2.00. *Continuation of well known and valuable series; statistics for 1937.*

Structure and Gas Possibilities of Oriskany Sandstone in Steuben, Yates and Adjacent Counties, New York. W. H. BRADLEY AND J. F. PEPPER. Pp. 68; figs. 7. U. S. Geol. Surv. Bull. 899–A, 1938. Price, 35 cts. *Detailed stratigraphy and structure; oil and gas possibilities.*

Geophysical Abstracts, 90, July-Sept., 1937. W. AYVAZOGLOU. Pp. 43. U. S. Geol. Surv. Bull. 895–C, 1938. Price, 10 cts. *A continuing series.*

Quebec Bureau of Mines, Ann. Rep. for 1936. Part A. Mining and Statistics. Pp. 166. Ottawa, 1937.

Alunite Deposits of Marysvale, Utah. E. CALLAGHAN. Pp. 134; figs. 4. U. S. Geol. Surv. Bull. 886–D. 1938. Price, 15 cts. *Geology and descriptions of vein and replacement alunite.*

Geology of Bay St. George Carboniferous Area. A. O. HAYES AND H. JOHNSON. Pp. 62; pl. 5; figs. 17. Newfoundland Geol. Surv. Bull. 12. St. Johns, 1938. *General geology, coal, gypsum, peat, clays, waters.*

Copper Mining in North America. E. D. GARDNER, C. H. JOHNSON, B. S. BUTLER. Pp. 300, figs. 92. U. S. Bur. Mines, Bull. 405. 1938. Price, 40 cts. *Comprehensive; history, geology, prospecting, exploration, development and mining; excellent brief treatise.*

Stratigraphic and Paleontologic Studies of Pennsylvania and Permian Rocks in N.-Central Texas. W. LEE, C. O. NICKELL, J. S. WILLIAMS AND L. G. HENBEST. Pp. 252; pl. 9; figs. 9. Texas Bur. Econ. Geol. Univ. Texas Pub. No. 3801. Austin, 1938. Price, $1.50. *Careful, comprehensive study of stratigraphy and fauna.*

Subsurface Geology of Oil and Gas Resources, Osage Co, Oklahoma. N. W. BASS, L. F. KENNEDY, W. R. DILLARD, O. LEATHERROCK AND J. H. HENGST. Pp. 45; figs. 2. U. S. Geol. Surv. Bull. 900–A. 1938. Price, 30 cts. *Detailed by townships.*

Geology and Ore Deposits of S. W. Arkansas Quicksilver District. J. C. REED AND F. G. WELLS. Pp. 90; pl. 16; figs. 11. U. S. Geol. Surv. Bull. 886–C. 1938. Price, 75 cts. *Details of geology, structure and cinnabar deposits.*

Barite in the Tennessee Valley Region. W. J. PENHALLEGON. Pp. 47, T. V. A. Geol. Bull. 9. Knoxville, 1938. *History, geology, mining, milling of various barite districts.*

Iron, Chrome, and Nickel Resources of the Tennessee Valley Region. E. C. ECKEL, C. E. HUNTER, P. W. MATTOCKS. Pp. 26; pl. 4. T. V. A. Geol. Bull. 10. Knoxville, 1938. *Geology, reserves and descriptions of raw materials and deposits of hematite, limonite, magnetite, chrome and nickel.*

Mineral Exportations in Peru, 1937. J. HOHAGEN. Pp. 396. Cue. Ing. de Minas, Bull. 120. Lima, 1938. *Statistics of production and exportation.*

My Last Expedition to the Antarctic, 1936–7. LARS CHRISTENSEN. Pp. 16. J. G. Tanum, Oslo, 1938. *Interesting lecture of exploration and discovery; magnificent aerial pictures.*

Geological Survey of Part of N. W. District, Br. Guiana. S. BRACEWELL. And appendix on **Geology of Aruka District.** W. T. Lord. Pp. 37; maps. Br. Guiana Geol. Surv. Bull. 7. Georgetown, 1938. Price, 24 cts. *General geology and placer gold deposits.*

Aremu and Peters Mine Areas, Br. Guiana. D. W. BISHOPP. Pp. 20; maps. Br. Guiana Geol. Surv. Bull. 9. Georgetown, 1938. Price. 12 cts. *General geology; lode and placer gold deposits.*

Cranbrook Map-Area, British Columbia. H. M. A. RICE. Pp. 67; pl. 3; geol. maps. Can. Geol. Surv. Mem. 207. Ottawa, 1937 (Oct. 1938). Price, 25 cts. *General geology of section of Rockies; large faults; gold placers, the famous Sullivan mine, and other mineral deposits.*

Thetford, Disraeli, and Eastern Half of Warwick Map-Area, Quebec. H. C. COOKE. Pp. 160; pl. 1; figs. 26, geol. maps, 4. Can. Geol. Surv. Mem. 211. Ottawa, 1937 (Oct. 1938). Price 50 cts. *General geology and petrology of asbestos rocks; occurrence and origin of asbestos; chromite.*

Gold Placers of the Fortymile, Eagle, and Circle Districts, Alaska. J. B. MERTIE, JR. Pp. 128; pl. 5, figs. 2. U. S. Geol. Surv. Bull. 897–C. Washington, 1938 (Oct.). Price, 20 cts. *General geology; gold originally in granites, concentrated in tertiary conglomerates (analagous to the Rand), then into placers.*

Geology of the Marathon Region Texas. P. B. KING. Pp. 148; pl. 24; figs. 33. U. S. Geol. Surv. Prof. Pap. 187. Washington, 1938 (Oct.). Price, $2.50. *Careful, detailed stratigraphy of Pre-cambrian, Cambrian, Ordivician, Devonian, Pennsylvanian, Peruvian, Cretaceous; large structural features; thrust faults; excellent.*

Bradford Oil Field (Penn. and N. Y.) C. R. FETTKE. Pp. 454; pl. 21; maps, 5. Penn. Geol. Surv. Bull. M21. Harrisburg, 1938 (Sept.). Price, $3.00. *Areal and subsurface stratigraphy and structure; occurrence and descriptions of oil and gas pools; natural and flooding production; excellent report.*

Oligocene Foraminifera from Choctaw Bluff, Alabama. J. A. CUSHMAN AND WINNIE MCGLAMERY. Pp. 25; pl. 5. U. S. Geol. Surv. Prof. Pap. 189–D. Washington, 1938 (Oct.). Price, 10 cts.

SCIENTIFIC NOTES AND NEWS

PHILIP J. SHENON who has been with the U. S. G. S. in Idaho is now in the geological department of the International Nickel Corp. at Copper Cliff, Ontario.

JOHN G. BARAGWANATH, president of Pardners Mines Corp. in New York City, has been elected recently to the Board of Directors of Dome Mines, Ltd., South Porcupine, Ontario.

EDWARD WISSER, mining geologist of the firm of Bryan, Wisser and Payne consulting engineers of Manila, is in charge of the San Francisco office of the company at 533 Call Building.

WILLIAM J. LORING has resigned as director and president of the Arizona Comstock Corp. to enter private practice connected with the development and financing of mining properties.

HENRY E. GOSS, who has been assistant professor of petroleum engineering at the University of Oklahoma will be on the faculty of A. and M. College of Texas this year.

E. L. BRUCE has returned to Kingston, after completing the summer's field work in the Michipicoten area of northern Ontario.

FREDERICK G. CLAPP, consulting petroleum geologist of New York City, returned to his old office, 50 Church Street, in September after several years in the Near East.

R. H. HUNT is now in charge of the Western Exploration department of U. S. Smelting, Refining and Mining Co. with offices in the Newhouse Building, Salt Lake City.

GEORGE W. STOSE and MISS ANNA I. JONAS were married at the home of Prof. and Mrs. Adolph Knopf in New Haven, on Sept. 13th. They will be at home in November at Arlington, Virginia.

L. KENNETH WILSON, who has been assistant geologist for Eastern Exploration Co. in Goldfield, Nevada, is now resident manager of the Auburn Chicago Mining Co. at Penryn, California.

GEORGE R. MANSFIELD, geologist of the U. S. Geological Survey, is laid up at his home in Washington with a broken leg. He was kicked by a horse while doing field work this summer.

R. M. PETERSON is being transferred from Roan Antelope Copper Mines, Ltd., to be manager of Mufulira Copper Mines, Ltd., and will take charge December 1.

WILLIAM E. WRATHER, consulting geologist of Dallas, Texas, is convalescing from an operation.

SYDNEY U. BARNES has gone to Cairo, Egypt, for the Standard Oil Co. of Egypt.

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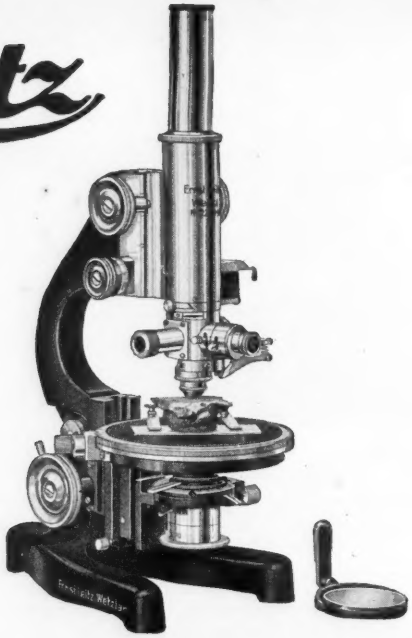

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